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# FUTURE POSSIBILITIES OF THE SUPERSONIC TRANSPORT PLANE

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# FUTURE POSSIBILITIES OF THE SUPERSONIC TRANSPORT PLANE

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by

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SUMMARY

Within the next ten years transport aircraft flying at speeds from 1243 to 2175 m.p.h. (2000 to 3500 km.h.) will probably take over from the existing jets on certain well-travelled air routes. New technical problems posed by such planes are rapidly reviewed before touching on the economic, operational, and human aspects of supersonic flight. Finally, the probable characteristics of two types of planes currently under consideration, long-range Mach 3 and medium-range Mach 2 airliners, are given as examples.

## I. INTRODUCTION

Before getting to the numerous problems raised by introducing supersonic transports (S.S.T.) into service, it would be useful to place this supersonic domain in the framework of the speed range achieved by man in the chronology of aeronautical development and in the range of flight durations.

1. Our speed scale (fig. 1) now extends from zero (the vertical lift of V.T.O.L. craft) to 25,000 m.p.h. (40,000 km.h.) (escape velocity from the earth's gravity) and the supersonic domain occupies a very modest place in the range from 808 to 3293 m.p.h. (1300-5300 km.h.) (from Mach 1.2 to Mach 5, the Mach number being the relationship of flight speed to the speed of sound, here taken to be equal to 662 m.p.h. (1065 km.h.) in the stratosphere). We shall see that the usable cruising-speed range for an S.S.T. is even more limited -- approximately between Mach 2 and Mach 3.

Actually, in the following material we will also have to take into consideration the behavior of the aircraft in the subsonic and transonic regions through which the S.S.T. must pass when entering and leaving the supersonic domain. Thus, in the next five years civil aviation will have at its disposition four basic types of effective and economically operable craft:

-- The heavy helicopter for civil missions requiring vertical lift;

-- Short takeoff aircraft (S.T.O.L.) of the Breguet 941 type, able to fly at speeds ranging from 56 to 311 m.p.h. (90 to 500 km.h.) on feeder lines serving small airports close to cities or in the mountains;

-- Medium- or long-range subsonic aircraft with cruising speeds ranging from 497 to 621 m.p.h. (800 to 1000 km.h.). Most civil airlines will be equipped with this type of craft which shows high hopes for the future in safer and more economical operation;

-- Medium- and long-range supersonic transports flying at Mach 2 and Mach 3 (1243 to 1864 m.p.h. - 2000 to 3000 km.h.).

2. In the scale of time (fig. 2), the supersonic region was first entered on the fourteenth of October, 1947 by Charles Yeager, aboard a N.A.C.A. experimental aircraft, Bell X-1, which reached a Mach number of /190
1.06 and then five months later, Mach 1.47, e.g., 963 m.p.h. (1550 km.h.). In that year aviation entered a new era, only three years after the first jet airplane had been put into service. The birth of jet propulsion had actually enabled man to achieve speeds heretofore inaccessible to propeller-driven planes, but for several years pilots were faced with poorly understood aerodynamic phenomena without the aid of sufficiently developed aeronautical science. That was why the ten-year period from 1945 to 1955, was fairly comparable to that of aviation pioneering, with its long list of dead among test pilots.

The prowess of the experimental planes was succeeded by the remarkable performances of operational military aircraft and at this point we ought to mention Colonel ROZANOFF who was, in October of 1952, the first in France to cross what was then called the "wall of sound" on board a Mystère II. On that occasion the ground observers were surprised by a mighty clap of thunder -- the famous "boom" which was for some time the big attraction of airshows to the detriment of the windows of the local populace. We shall have occasion to speak of this again further on.

During this period civil aviation took advantage, after a certain time lag, of the technical progress of military aviation. A study of the time lapse between the speeds attained respectively by prototype bombers and commercial transports is quite instructive. The four-motored B-17 and B-29 bombers, famous during the last war, were succeeded by the long-range airliner DC 4, DC 6, Constellation, and finally, the DC 7. Then came the era of jet propulsion opened in 1947 by the B-47 bomber, but ten years had to pass before the appearance of the first operational flight of the long-range jetliner, the Boeing 707, followed by the DC 8 and the Convair 880.

And now? If we consider this ten-year time spread still valid, the introduction of supersonic transports into service follows inevitably in 1968 and 1973 since the B-58 flew at Mach 2 in 1958 and the B-70 bomber, Valkyrie, will fly at Mach 3 at the end of this year.

Thus we must submit to the evidence: The supersonic transport is at hand for the near future!

3. Flight duration is an essential idea in transportation for both user and operator. The former wishes to get where he is going as quickly as possible, while the latter is interested in making the largest number of trips per day in order to increase his operational efficiency.

Increasing the cruising speed of an airplane results in important time savings which increase in value with increasing flight length, since the "dead time" (servicing, embarking passengers on the ground, takeoff, climb, descent, holding, and landing, not forgetting administrative formalities and customs) remains substantially the same. Unfortunately the flight time does not vary inversely with cruising speed and mere speed is of no appreciable advantage for short flights or at high Mach numbers. To tell the truth, our Earth has gotten too small to permit the use of commercially economic aircraft flying at hypersonic speeds on the order of 4350 m.p.h. (7000 km.h.) since the demand for nonstop flights of more than 6214 miles (10,000 k.) is not sufficient to justify studying the possibilities of such a plane which would, moreover, raise enormous technical problems. Let us, then, immediately establish the gamut of speeds to be considered and their effects on the flight time from Paris to New York (3418 miles - 5500 km.) compared with those of a few years back or of the present (fig. 3):

| | Mach number | Cruising speed | Flight duration | Entered into service |
|---|---|---|---|---|
| Four motors, reciprocating engines (Douglas DC 7)------- | 0.53 | 351 m.p.h. (565 km.h.) | 14 hrs | 1956 |
| Four jet, subsonic (Douglas DC 8)------- | 0.86 | 568 m.p.h. (915 km.h.) | 7 hrs | 1960 |
| Future supersonic transport------------ | 2 | 1324 m.p.h. (2130 km.h.) | 3-1/2 hrs | |
| | 3 | 1988 m.p.h. (3200 km.h.) | 2-1/2 hrs | |

Thus we see that putting the existing subsonic jets into service has halved the time for crossing the Atlantic and also that the future supersonic jet, the S.S.T., will more than halve this time again. Moreover, the shape of the curve in figure 3 shows that the block-to-block time, i.e., the time from the loading of passengers to their unloading, will hardly be reduced by speeds any greater than Mach 3.

Under these conditions, a single Mach 3 aircraft could theoretically make six Atlantic crossings every day carrying 120 passengers each time. In the same manner, this plane could make a daily round-the-world flight "following the sun" in an east-west direction leaving /191 Los Angeles at 6 p.m. and returning there the following day, having made service stops at Honolulu, Tokyo, Hong Kong, Karachi, and London.

Having compared the performances of long-range airliners of the past, present, and future, it would now be interesting to show the differences in the percentages of their total weights devoted respectively to useful load, to fuel, and to structure. While useful load and fuel each represented 25% of the total takeoff weight of a propeller-driven long-range aircraft (turboprop), the useful load drops to 14% for existing subsonic jets and will be hardly more than 8% of the total weight of a Mach 3 S.S.T. On the other hand, the fuel's share goes up to 46% for the subsonic jet and to more than half of the takeoff weight of the S.S.T. This indicates that for a given number of passengers, the supersonic transport will have to be much heavier than the planes of the present or of the recent past. And above all this indicates that the commercial success of the S.S.T. will be extremely sensitive to the slightest error in calculating fuel consumption or the weight of the airframe and engines.

It is to be recalled that the takeoff weight of a four-turboprop plane of the Britannia type is on the order of 88 tons (80 Metric tons), that of the Boeing 707 about 143 tons (130 Metric tons) and that of the future Mach 3 long-range S.S.T. will be at least 198 tons (180 Metric tons), all three carrying approximately 120 passengers. Against this, a "medium-range Mach 2 airliner" for 100 passengers ought to weigh half again less.

For the engineer and the pilot, the supersonic domain is already familiar territory since many military craft (fighters and bombers) have access to it, while missiles cross through it. However, no person has as yet stayed there for any appreciable length of time since supersonic flight is expensive and causes a progressive heating of the shell of the plane. Thus, having hardly crossed the sonic barrier, we are going to find ourselves facing the "thermal barrier."

In spite of all these new problems to be solved, the aeronautic research organizations of several countries are currently working on plans for supersonic transports which will take over from existing subsonic jets on certain well-travelled routes within ten years. Because of the amount of technical and financial support needed to develop such an airplane, its construction represents an effort which will engage the national prestige of a country in the same way as success in spatial exploration.

In conclusion, the matter at hand is not whether this airplane will or will not be built, but rather how best to build it so that its operation will be safe, reliable, and economic. At this point, we must touch on the technical aspects of supersonic flight and, first of all, on the heat problem at high speeds.

## II. APPROACHING THE THERMAL BARRIER

In order to thoroughly understand the process of surface heating of aircraft flying at increasing speeds, let us examine the flow of air around a wing airfoil. Among the "flow lines" or fluid streams flowing around the airfoil, those closest to the surface contribute to the formation of a boundary-layer which develops on both sides and gives rise to friction resistance (drag). One of these flow lines comes directly into the leading edge of the airfoil and at this "stagnation" point speed disappears. All the kinetic energy contained in this fluid stream has been abruptly cancelled, but in virtue of the principle of the conservation of energy, this kinetic energy is transformed into heat. Heating at the stagnation point will be proportional to the square of the flight speed. At the speed of the Caravelle, 528 m.p.h. (850 km.h.), this heating is only about 25° C. with respect to the ambient temperature at the altitude of flight, which is to say completely negligible. On the other hand, for a "Mirage III" flying at Mach 2, i.e., 1323 m.p.h. (2130 km.h.), this heating exceeds 170° C. and, as the ambient temperature above 68,350 ft. (11 km.) is some -56° C., the forward surface of this plane is heated to more than 110° C.

The temperature at a point where the boundary layer touches the surface of the airfoil is less than that at the stagnation point, even though here, too, speed is cancelled out, but the reason is that one part of the heat, in those layers most subject to friction heating, is dissipated by conduction to the relatively cooler layers. If we were to imagine a skin surface perfectly impermeable to heat and with no radiation loss, the frictional heating would only be 85 to 90% of heating at the stagnation point, depending on whether the boundary layer were laminar or turbulent. /192

In reality the surface is never perfectly insulated and a part of the heat lost by the boundary layer is going to move by convection through the skin and heat not only all the structural elements but also the fuel stored in the wing. Conversely, a part of the heat absorbed by the surface material will be dispersed back into the atmosphere by radiation. Finally, if the flight lasts long enough (which will be the case with our supersonic transport), there will be established an ultimate thermal equilibrium (balance of convected and radiated heat flows) which the engineer will have to calculate and verify through tests in order to choose those materials capable of supporting this equilibrium temperature without losing their structural properties.

To give an example, figure 5 furnishes the range of equilibrium temperatures reached on the surfaces of a supersonic transport flying in the stratosphere at speeds between Mach 1 and Mach 4:

-- At Mach 2.2, this temperature may reach 150° C. locally, while at Mach 3 the hottest point will get to about 320° C. The temperature map at different points on the airplane and on the jet engine will also reach that figure.

Over and above the problem of cooling the cabin and fuel, which we will bring up later, such temperatures may affect the mechanical properties of the materials and, in addition, those of the transparent surfaces and equipment on board. The nonmetallic components may well be the most heat critical.

The problem presents even more difficulty because this airplane is destined for commercial use and will, to be economically feasible, have to last about 20,000 hours with alternating heat and cold causing rapid expansion in the course of the flight (and particularly in the descent). We do not yet know how materials age under such conditions, but we do know already that it will be impossible to use existing light alloys above a temperature of approximately 150° C. For higher speeds we must call on titanium-based alloys usable up to 300° C., or stainless steel which retains its structural strength up to 700° C.

Most of the fuel will be carried inside the wing and, in flight, will progressively heat up to temperatures of some 70° C. at Mach 2 and 120° at Mach 3 at the end of cruise. In this latter case it may be necessary to use a special, more costly kerosene. Under these conditions, fuel cost becomes an important part of the direct operating costs of these planes.

The French and British choice of a transport flying at Mach 2.2 is in large part motivated by the possibility of using light alloys (special duralumins) for a large part of the skin of the plane. It is possible that use of titanium could lead to lower structural weights but the cost of the plane would be higher (more expensive raw material and machining).

Finally, stainless steel, necessarily in a sandwich-type skin, costs a great deal and is not justified except in the neighborhood of Mach 3. This solution was adopted by the Americans for the B-70 bomber and also for their projected Mach 3 supersonic transport.

By definition, the air scooped into the intake of turbojets is at a stagnation temperature corresponding to the flight Mach number (i.e., 110° C. and 330° C for flights in the stratosphere at Mach 2 and Mach 3). Thus, the temperature level in the compressors would be higher than in subsonic aircraft, whence the indispensability of using stainless steel for all compressor vanes.

## III. PERFORMANCE IN SUPERSONIC FLIGHT

Since we are here concerned with a commercial rather than a military plane, efficiency of performance is of vital concern and gives rise to the question, "What price will have to be paid for speed?"

1. As is the case with subsonic flight, the answer is largely to be found in Breguet's classic equation reflecting the flight performance of a long-range airliner (fig. 6).

Ultimately range depends on three essential factors:

a. The importance of aerodynamics is based on aerodynamic efficiency (Cx/Cz) or the Lift/Drag ratio, i.e., the weight of the aircraft to the thrust necessary for straight and level unaccelerated flight. We shall see that aerodynamic efficiency at supersonic speeds is, unfortunately, markedly inferior to that of existing aircraft in subsonic flight.

b. Propulsion comes in through the ratio of speed to specific fuel consumption which equates to the overall thermal efficiency of the propulsion system (transformation of fuel energy into thrust). We shall see that thermal efficiency increases with flight speed.

c. Structural weight as well as that of the propulsion units and auxiliary equipment, which figure into the initial and final weight ratios for cruising:

$$\frac{P_i}{P_f} = 1 + \frac{P_c}{P_f}$$

and ultimately determine the weight of fuel which the plane can carry (this is the well-known "mass ratio" so familiar in the study of ballistic missiles and rocket launchers). /193

Kinetic heating may bring about a trying reduction of this ratio due to added structural weight and to the refrigeration equipment necessary at high Mach numbers.

The problem is broadly presented in figure 7c where we see that the performance, e.g., the range factor of Breguet's equation, first drops sharply in the transonic region and then rises again throughout the supersonic range to the point where it approaches that of existing jets. This is strictly the result of increased speed since aerodynamic efficiency and specific consumption of the jet engines both suffer losses in the supersonic domain.

In passing let us note the abrupt drop in aerodynamic efficiency when existing jets penetrate the transonic region but also the remarkable progress already made in that field from the first generation fighters and bombers to aircraft in the development stage, such as the B-70. Such progress requires extremely advanced research in aerodynamics (theoretic calculations followed by systematic wind-tunnel experimentation (fig. 7d)).

2. Supersonic aerodynamics is one of the best-known branches of aeronautical technology and is grounded on solid theoretical bases well tested in both wind-tunnel and flight experience. /194

Let us take a look at the parameters governing aerodynamic efficiency in the supersonic range.

To the drag caused by friction and that tied to lift, both previously encountered in subsonic flight, must now be added the wave drag bound to the thickness of the body and a parasite drag which is more intense than in the subsonic range and is a function of the longitudinal trimming of the aircraft by means of an elevator control.

Thus the four principal elements of drag are the following:

a. Friction drag of the same order as that encountered in subsonic flight. Because of the extreme speed and probable dimensions of the aircraft, the "Reynolds number" is such that the boundary layer will be turbulent over almost the totality of the flow surfaces of the airplane, but friction will be relatively less here than with existing aircraft due to highly polished surface areas. Total friction drag may be minimized by reducing the size of the wing (increasing the wing loading) but we shall see that such a reduction is limited by landing requirements. Current research also indicates the possibility of reducing both friction and heating by means of ejecting a fairly small amount of air along the surface.

b. Wave drag is primarily governed by the degree of streamlining or "relative slenderness" of the components of the aircraft. Thus, for a given shape, wave drag increases as the square of the relative thickness of the wing and tail, whence the interest in extremely thin wings up to the point where prohibitive structural weight is needed to provide sufficient strength.

Fuselage wave drag also decreases as nose streamlining is increased, necessitating the adoption of very pointed shapes interrupted, unfortunately, by the cockpit (we are thinking of covering it with a hood and opening it only at subsonic flight for takeoffs and landings).

Elsewhere, the drag wave is reduced as the wing is swept back and since large aspect ratio is of no value in supersonic flight, as we shall see below, we are moving toward shapes of the type of a sharp delta with a small span, which configuration has the added advantage of good structural rigidity even with very thin wings (most existing supersonic planes have wings with thickness/chord ratios of between 3 and 4% while the subsonic jets have ratios of 10 to 12%). Besides, theoreticians know how to calculate distributions of thickness and volumes to minimize this wave drag.

Finally, the wave drag coefficient diminishes slightly as the Mach number increases.

c. Induced drag as a function of lift increases as the square of the latter but, contrary to the two preceding elements, it increases with the Mach number. Induced drag also depends on the sweepback angle of the leading edge of the wing. If the leading edge is inside the "Mach cone" issuing from the point where the wing joins the fuselage, it is called "subsonic" since the component of normal speed on the leading edge is effectively less than the speed of sound. In this case it is possible to calculate a profile camber which markedly reduces induced drag. This conical camber of the leading edge is quite visible on a number of high-speed aircraft and in particular on the delta winged "Mirage III" and "Convair B-58" with their leading-edge sweepback of 60°. The performances and flight qualities of these craft are highly improved with respect to a "flat" wing so long as their leading edge remains "subsonic," i.e., below Mach 2. Of course, for very high cruising speeds it would be necessary to make very sharp sweepbacks in order to remain "subsonic" (for Mach 3 the leading edge sweepback would have to be more than 70°) while the advantages with respect to drag would be too small to justify such a choice, whose disadvantages we would see at low speeds. Only a wing with variable sweepback would permit perfect adaptation of the aircraft to all speed regimes.

At this point it would be interesting to compare total drag at increasing Mach numbers (fig. 8):

-- The existing jet with its thick airfoil to permit housing the structure of its high aspect-ratio wing meets the onset of transonic troubles between Mach 0.8 and Mach 0.9 according to the type of airplane. Above these "critical" Mach numbers, the formation of shock waves along the wing surface brings on a variety of troubles (vibrations, inversion of the control pattern, etc.) and, most importantly, a sharp increase of drag. Thus this type of plane is sentenced to rest at the "foot of the wall of sound."

-- Conversely, the S.S.T., very slender and with thin wings swept back sharply, is hardly troubled at all when crossing the sound barrier but its drag is sufficiently increased to necessitate pushing the motors to the limit, or even the temporary use of an afterburner behind the turbines.

Cruising altitudes, which must obviously correspond to flight in the region of maximum aerodynamic efficiency, differ greatly from subsonic to supersonic flights (fig. 9). The existing jet, although heavily loaded, must fly relatively high, around 32,800 feet (10,000 meters), because of its large aspect ratio (maximum aerodynamic efficiency $\cong$ 19). The S.S.T., either cruising or in a holding pattern at the subsonic speed of Mach 0.92 (i.e., at the base of the sharp increase in drag) will also fly at that altitude (maximum aerodynamic efficient $\cong$ 12). But, in supersonic cruise at Mach 2.2 the optimum altitude will vary from 59,000 to 65,600 feet (18,000 to 20,000 meters), which is double the preceding altitude (maximum aerodynamic efficiency $\cong$ 8). We shall see that this altitude has the additional advantage of limiting the intensity of the sonic boom reaching the ground.

d. The problem of the longitudinal trim of the S.S.T. is more difficult than for the subsonic airplane and this is chiefly due to the fact that the stability of aircraft increases sharply with passage of the transonic region (fig. 10). There results a reduction of maneuverability in the supersonic domain which means that the controls must be set at a greater angle to maintain aircraft trim while cruising, whence a sharp rise in drag. Several solutions have been proposed to minimize or completely cancel this increase of stability in the transonic range: /195

-- A "floating" canard foreplane, i.e., mounted as a freely revolving vane at subsonic speeds but immobilized in the supersonic range to reduce stability.

-- Wingtips designed to fold downward in supersonic flight, as on the B-70 bomber, would reduce longitudinal stability but in addition would let these wingtips assist in flightpath stability which is very marginal at high Mach numbers (since the unitary lift of the wing surfaces rapidly decreases as the Mach number increases).

-- A rear empennage which could be folded downward in supersonic flight to act as fins participating in flightpath stability.

-- And finally, transfer of a part of the fuel in the tanks from front to rear would allow reduction of stability in supersonic flight (solution adopted for the B-58 bomber).

Other more classic methods are used to trim the plane in supersonic cruise (fig. 11) by adapting the shape of the fuselage nose cone (curved upward, unfortunately for pilot visibility) or by drooping the airfoils along the span of the wing (twisted/cambered shapes) or by maneuvering the classic controls (this last solution would be much more costly in terms of drag). Longitudinal trim of the plane at low speeds, and in particular under conditions of the large lifts necessary for takeoffs and landings, may be obtained by a negative angle of the elevons or tail surfaces or by a positive setting of the canard foreplanes, or finally by discharging a jet under the nose of the fuselage (the idea of a grouping of lifting jets situated in the forward part of the fuselage and fired during takeoff and landing is not inconceivable and might give this plane S.T.O.L. characteristics).

Concluding this section, the reduction of drag forces in supersonic flight requires an extremely fine scientific base on the part of the theoreticians and a great deal of architectural prowess on the part of the planemaker, but it is only under these conditions that a /196 supersonic transport would be viable. To be convinced, one has only to consider (fig. 12) the loss of aerodynamic efficiency brought about by failing to observe the most favorable conditions united for a plane "optimized" to fly at Mach 2.2. Let us note that in this "calculated" example, friction represents 39%, wave drag 16% and external resistance of the propulsion group 12%.

3. The development of propulsive efficiency in supersonic flight.

We have seen (fig. 6) that the second term intervening in the calculation of the range of a jet plane was the ratio of cruising speed to specific consumption of the engines ($V_o/C_s$).

The consumption of jet engines, expressed in kilograms of fuel burned per hour per kilogram of thrust, shows a marked increase in passing from subsonic to supersonic flight (fig. 7b):

-- For the existing subsonic jet flying at Mach 0.85, this consumption is less than, or equal to, 0.9 while for supersonic transports at Mach 2 and Mach 3 we can predict consumptions corresponding to $C_s$ of about 1.3 and 1.6 respectively (fig. 7b).

Nevertheless, and this is fortunate for the future of the supersonic transport, the $V_o/C_s$ ratio increases considerably with the Mach number and compensates for the loss of aerodynamic efficiency when crossing the sound barrier, in Breguet's equation for range. At Mach 3 we have nearly gotten back to the rate achieved by existing subsonic jets (fig. 7c) whose commercial exploitation is considered economically feasible. Thus we see once more that speed pays and this is quite simply explained by the fact that the overall thermal efficiency of jet engines increases with speed (fig. 13). By definition, the thermal efficiency of any machine is the ratio of work output to energy contained in the fuel burned. This is precisely our term $V_o/C_s$ calculated above. Thus the thermal efficiency of a jet engine is only 23% in a plane at Mach 0.85, but it rises to 37% at Mach 2 (which is better than the thermal efficiency of the best of existing electric power plants) and to 46% at about Mach 3. Moreover, with ramjets in the hypersonic range this efficiency continues to increase.

Supersonic flight can, then, be economically feasible. Now let us take a look at the available jet engines.

From the ordinary turbojet to the pure ramjet there exists a whole gamut of intermediary solutions resulting from a compromise between the performances desirable throughout an entire mission (takeoff, climb, crossing the sound barrier, cruising) and tolerable noise level at takeoff. We are all aware that the use of the turbofan, or two-flow jet engine is going to become generalized in existing jets because of its increased thrust for takeoff and climb, but also because of the reduced specific consumption while cruising. The turbofan engine also has a lower exhaust velocity resulting in a more tolerable noise level at takeoff. These jet engines can be used in supersonic flight by the expedient of increasing the exhaust velocity of the secondary flow by heating it again with a crown of burners in the plenum chamber. However, the "classic" single-flow jet engine is still competitive for Mach 2 aircraft.

For a civil aircraft which is to fly at supersonic speed for periods from one to two hours, the "reheating" must be adjusted to the best level for each Mach number. It will be relatively moderate -- or even useless -- for cruising, but momentarily intense during the acceleration at the passage of the sound barrier (this is actually the most critical moment and may ultimately condition the type of engine chosen).

Towards Mach 3, the turbofan engine with afterburner meets competition from the turbo-ramjet since air compression due to speed alone is sufficient if not to put the compressor out of action, at least to slow it down.

Above Mach 3, the heating due to compressibility effects is also enough that it becomes difficult to use the turbines and so this is the domain of the pure ramjet whose efficiency, moreover, becomes excellent here.

Aerodynamics intervenes directly in the matter of propulsive efficiency by the effectiveness of the compression in the air-intake duct (fig. 14):

-- If compression is carried out across a normal shock wave, the loss of intake efficiency becomes catastrophic at high Mach numbers. Thus we are led to break down this recompression through one or several oblique shock waves to minimize energy loss and approach the ideal "isentropic" recompression. Figure 14 shows that for a well-adapted air intake, the pressure at engine entrance is respectively nine and 26 times the ambient pressure for flights at Mach 2.2 and Mach 3. /197

Such air intakes may be of revolution with an emerging point (B-58 bomber), of half-revolution against the fuselage (fighters F-104, Mirage III and IV), or "bidimensional." This latter configuration, in which recompression is carried out on a double inclined plane, which creates oblique shock waves, allows a better integration of the propulsion group into the airframe and will probably be adopted by the supersonic transports. A schematic drawing of the entire propulsion group (figs. 13 and 14) illustrates the complexity of mechanisms permitting continuous adaptation[1] of the intake and nozzle cross sections as a function of flight speed. Ultimately this complexity is justified by the necessity for high propulsion efficiency at all Mach numbers throughout the flight.

## IV. THE TRANS-ATLANTIC FLIGHT AT SUPERSONIC SPEED

At this point it would be valuable to sketch in (fig. 15) the flightpath of a transport at Mach 2.2 on the London-New York route (3418 miles - 5500 km.).

For a takeoff weight of 165 tons (150 Metric tons), the fuel makes up 45% and the useful load only 10% (120 passengers plus crew). The other 45% represents the empty weight of the plane (including the six turbojet engines with static jet thrust on the order of 61 tons (55 Metric tons), i.e., 37% of the takeoff weight).

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[1] At the intake, the inclination of the inlet ramp is "subjected" to the flight Mach number so that the oblique shock wave will fall on the opposite lip of the cowling. The subsequent subsonic flow is again compressed in a diffuser giving into the compressor. After leaving the turbine, the gases are reheated, if necessary, in an afterburning chamber and then accelerated in a variable nozzle and finally mixed with a secondary flow which had circulated around the turbojet engine. The "traps" permit elimination of the boundary layer at critical points.

a. The takeoff poses no technical problems as the thrust of the engines is sufficient so that a very high acceleration is possible even at less than "full throttle" (to reduce the takeoff noise level).

b. The climb must necessarily be effected at subsonic speeds up to about 36,100 feet (11 km.) (below that altitude sonic-boom damage to the surrounding populace is unacceptably high). Thus at Z of 36,100 feet (11 km.), the plane accelerates from Mach 0.9 to Mach 1.1 even though it would be much more economical to cross the sonic barrier at a lower altitude.

Then, at initial cruise altitude (Z of 55,777 feet - 17 km.) it quickly accelerates to Mach 2.2. At this point, one-half hour after takeoff, the plane has flown some 375 miles (600 km.) and has already used 21% of its fuel.

c. The craft cruises at a constant Mach 2.2 (i.e., 1454 m.p.h. - 2340 km.h.) with an estimated head wind of 56 m.p.h. (90 km.h.) and a slightly increasing altitude (from 55,777 to 62,339 feet - 17 to 19 km.) in order to fly at a constant aerodynamic efficiency[2] as the aircraft lightens up. Thus it covers about 2796 miles (4500 km.) while using 54% of its fuel with its cruising time being about two hours.

d. The craft descends over 250 miles (400 km.) at a decreasing speed, crossing the sound barrier, as in the climb, at about 36,100 feet (11 km.) in order to limit sonic-boom noise on the ground.

e. Under the most favorable conditions, the plane lands directly on the airport after a flight of 3418 miles (5500 km.) and three hours and ten minutes after takeoff, having used 83% of its fuel. /198

f. However, the safety rules of civil aviation could require a sufficient fuel reserve to permit diverting the aircraft to an airport 250 miles (400 km.) distant, preceded by a holding period of approximately one hour (a ruling on required reserves is already under discussion in the International Civil Aviation Organization (I.C.A.O.). This will be of decisive importance for the economic operation of the S.S.T., since the weight of the "reserve fuel" could exceed that of the useful load). Under these pessimistic conditions the plane lands after 4-1/2 hours in flight and having consumed 98.5% of its fuel.

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[2] With estimated aerodynamic efficiency here being $f = 8.1$, specific consumption of the engines $C_s$ 1.35 and the initial flight and terminal flight weight ratio of 149.8/109.7 tons (135/99.5 Metric tons) or 1.36, Breguet's equation enables us to calculate cruising range: $R = 2796$ miles (4500 km.) at a speed of 1454 m.p.h. (2340 km.h.).

To sum up, on this trans-Atlantic flight, the plane cruised at supersonic speed for 76% of the 3663 miles (5900 km.) flown, but in a time span representing only 45% of the overall flight time when there was a diversion and holding at the airport. It should again be noted that 45% of the fuel was consumed in purely subsonic flight.

Thus these figures show that acceptable performance is necessary in the subsonic regime (good aerodynamic efficiency and minimal fuel consumption at reduced speeds). Unfortunately the aerodynamic efficiency of sweptback wings in subsonic flight will at best be only 2/3 of that of existing jets with large aspect ratio, and that with extreme care in adapting the wing profiles. Once again we see that the most difficult problem for high-speed aircraft is to be efficient and acceptably safe at low speeds.

## V. CHOICE OF CONFIGURATION

A determining element in the choice of the wing-shape configuration is ultimately the landing speed, which the civil aviation safety rules will probably continue to limit to 140 knots, i.e., 1616 m.p.h. (260 km.h.) during final approach.

Wings with a sharp sweep angle and a narrow span, so desirable in supersonic flight, are little gifted for large lifts because of the limited lift increase to be gotten from increasing the angle of attack (fig. 16). As the acceptable limit of incidence during the approach and touchdown is on the order of 12° for reasons of visibility and ground-holding, the useful lift in the absence of high-lift flaps is ultimately very much less than that obtained on existing jets. It is to be remembered that the useful lift for jets having high-lift flaps is limited by the stalling conditions, safety rules requiring an approach speed 30% above stalling speed.

It is also possible to add flaps to a sharply swept wing, if the dive moment caused by the flaps is balanced by a rear empennage or, even better, by a fixed-angle canard which would become particularly effective if it were provided with a boundary-layer control system. This extremely attractive configuration does, however, give rise to some difficult problems of interference on the wings and fins.

Ultimately, four configurations are currently competing in the S.S.T. projects:

1. Tailless plane (or flying wing) type. This type receives no benefit from high-lift fins, but rather the opposite, since balance is achieved by a negative angle of the flaps. Useful lift is thus relatively small and necessitates a limited wing-loading on landing (less

than 41 lbs./sq. ft. - 200 kg./$m^2$). However, swept wings with a sharp leading edge benefit from a remarkable increase of lift thanks to the development of a vortex layer along the upper surface of the leading edge which creates an intense "inhaling effect" (fig. 17). This remarkable property of swept wings is especially valuable with wing shapes of ogival form and has given rise to profound research in England and France and led to the choice of the "flying wing" formula for S.S.T. projects at Mach 2.2 in both countries (fig. 21a).

2. The classic formula of rear empennage is currently used on the Soviet supersonic bombers from which a civil version might be drawn. /199

3. The "canard airplane" formula was chosen for the future American B-70 Mach 3 bomber. It allows some high lift on landing and facilitates trim in supersonic cruise. It is vaunted by several American aircraft builders for their projected Mach 3 long-range airliners (fig. 21b and c).

4. The solution by "variable-geometry wing" (fig. 19) has long been studied in England and then in the United States, and in particular by N.A.S.A. (fig. 21d). As supersonic cruise requires little aspect ratio and much sweepback while subsonic flight needs a large aspect ratio and moderate sweepback, the solution is to be found in pivoting the wing tips about a judiciously placed hinge to achieve a minimum variation of the thrust center during rearward folding. It only took someone to think of it.

It is obvious that such a solution demands an extremely heavy and complex mechanism which has to be able to withstand the heat generated by high speeds. Furthermore it becomes fairly difficult to store fuel in the wings, or at least in the mobile section.

Nevertheless, this solution may be globally satisfactory if it gives rise not only to comparable or better lifts than those of existing jets on landing but, most importantly, to excellent aerodynamic efficiencies during climb, transonic acceleration (the sweep of the wing is then about 50°), and holding. In particular, the plane might be economically operable in subsonic cruise if it were used on short flights, or if the sonic boom were absolutely intolerable in the flightpath regions. Finally, in the position of sharp sweepback, the surface is reduced and the Reynolds number increased, which results in reduced friction drag while the shape of the wing airfoils may be adapted to minimize induced drag.

The superiority of the "variable-geometry wing" with respect to the "delta-canard" type is obvious if we compare takeoff and landing performance (fig. 18).

Thanks to its large aspect ratio comparable to that of existing jets, but also to its thrust resulting in a greater acceleration and lower wing-loading, the S.S.T. with variable geometry would take off at comparable speeds but on a considerably shorter runway. Conversely, the delta-canard S.S.T., in the present example, would be marginal on the "standard" two-mile runway (3200 meters) and the takeoff speeds would be considerably higher. Obviously, these same tendencies would be observed in landing: the delta-canard S.S.T. is again marginal on existing international runways and it would be necessary to equip such a craft with thrust reversers to reduce runway speed. /200

Another difficulty for the swept wing with small aspect ratio is to be found in the obligation to carry out takeoff and approach in the "second regime," which is to say beyond the lift of maximum aerodynamic efficiency (thus a speed reduction requires an increase of thrust). In effect this necessitates the adoption of an automatic thrust control to assure speed stability during descent. We shall see further on that it would, in any case, be desirable to equip these planes with automatic takeoff and landing equipment.

## VI. UTILIZATION PROBLEMS

Putting the supersonic transport into service will give rise to numerous problems for the airlines -- and for governments. Mainly they will be problems of noise, safety, comfort, piloting, and routing.

1. The noise problem is certainly the most preoccupying, as it poses a question of the possibility of using these craft over inhabited areas. The sonic boom, produced by every plane crossing the sound barrier, is now universally familiar. It is caused when shock waves, generated by the plane, reach the ground. Figure 20 illustrates the fact that the observer on the ground hears the passage of the shock wave as a large "boom." The violence of this phenomenon can be measured by the amount of instantaneous pressure jump $\Delta_p$ which, according to its intensity, produces a sound of thunder or breaks all the windows in the area. A boom producing a pressure jump of 1 lb./sq. ft. (5 kg./m$^2$) sounds like distant thunder and should not aggravate the public. A pressure jump of 2 lb./sq. ft. (10 kg./m$^2$) begins to break windows and would certainly draw a loud protest from the inhabitants of cities flown over. Scientific study of the sonic boom is at present producing much research data. We already know that the pressure jump $\Delta_p$ varies little with the Mach number and increases with the size and wing-loadings of the aircraft, but most importantly, that it decreases with increase of flight altitude. In order that the disturbance does not go beyond tolerable levels, it will be necessary to climb to a fairly high altitude before crossing the sonic barrier, i.e., make a long climb at subsonic speed which is very uneconomical in fuel. Such a procedure is diagrammed

in figure 20 which shows the Mach number not to be exceeded at a given altitude while climbing, in order to limit the extent of damage on the ground. In this example (Mach 3 transport), the sound barrier is crossed in level flight above 36,100 feet (11 km.).

In supersonic cruise, calculations not yet completely verified by experience show that the intensity of the boom is of the same order for a Mach 3 aircraft as for one of Mach 2, since the greater weight of the former is compensated for by its higher flight level (68,900 feet as opposed to 59,060 -- 21 km. instead of about 18 km.). The pressure jump ought to be on the order of 1.6 lb./sq. ft. (8 kg./$m^2$) which comes close to the toleration limit and gives rise to serious consideration of forbidding supersonic flights over densely populated areas.

Theoretically, the jet noise at takeoff should be greater than with existing subsonic jets since the thrust rate will be higher. Actually it is just this "extra power" which will allow operation of the engines at less than full power (except in emergencies) so that the noise level ultimately ought to be comparable to that of existing jets.

On the other hand, this extra thrust at takeoff should permit a higher rate of climb and a sharper climbing angle so that the area subject to noise will ultimately be less extensive than at present. Moreover, it is possible that the noise problem while taking off and climbing will dictate the choice of turbofan jet engines for the future supersonic transport because of their lower noise level and good performance in subsonic climb. Passing the sonic barrier may eventually /201
necessitate the use of the afterburners to increase their thrust.

Finally, a third source of noise, which affects the aircraft itself, is the flow of air around the plane and more precisely the turbulent boundary layer. This noise, already evident on the shell of existing planes, will be very much amplified in supersonic flight. These microvibrations may generate dangerous structural fatigue of the metal and in addition may necessitate sound-proofing for passenger comfort.

2. Passenger safety and comfort.

We have seen that flight conditions for the S.S.T. are very different from those presently encountered:

-- A subsonic jet flies at a maximum altitude of about 36,100 feet (11 km.) and, outside the cabin, the air pressure is on the order of 1/4 of an atmosphere (3-1/2 lb./sq. in.) and the temperature in the neighborhood of -25° C. For a Mach 3 S.S.T. flying at 68,900 ft. (21 km.), the pressure at the exterior of the fuselage is on the order of 1/20 of an atmosphere (0.7 lb./sq. in.) and the temperature about 230° C. Thus the surface temperature is hot enough to "fry a steak" and the pressure low enough to "cause the blood to boil." In spite of these frankly extreme exterior conditions, we must maintain comfortable surroundings inside the cabin, i.e., a temperature of about 72° F. (22° C.) and a pressurization about equal to that on an altitude of about 6560 feet (2000 meters) (e.g., 11.2 lbs./sq. in. -- 8/10 of an atmosphere).

It is obvious that any rapid decompression, such as would be caused by a puncture in the hull, for example, means a death sentence for the passengers if no automatic compensating device has been provided. Fortunately, even at that altitude, the compression resulting from the plane's speed has a pressure of more than one atmosphere (14 lbs./sq. in.) and therefore simply opening an air scoop in the front of the plane will temporarily admit compressed air. As it will be scooped in at a temperature of some 320° C., it will have to be cooled by some device, as for example one which injects water. This emergency operation combined with the use of individual oxygen masks will permit a maximum limitation of passenger risk until the plane has had time to descend to an altitude in the neighborhood of 19,680 feet (6000 meters).

Actually, the fuselage will be calculated with a margin of safety sufficient to avoid such an incident.

Cabin air-conditioning raises another problem which will be easier to solve at Mach 2 than at Mach 3.

If the air necessary for pressurization were continually renewed by drawing in outside air, a veritable refrigeration plant would be necessary. The probable solution here will be recirculation of the cabin air (passed through a regeneration and cooling circuit), while any leaks would be compensated for by an emergency air scoop, thus benefitting from the high compression caused by the speed. The enormous mass of fuel could be used as a "heat-sink" for the refrigeration equipment. We have seen that the trans-Atlantic flight would only last about three hours. It would not, therefore, be necessary to provide a great deal of cabin luxury (increasing the cabin diameter is very expensive in supersonic flight). The future passenger will also be astonished by the steep incline of the floor during climb (about 17° trim) and by the tiny windows. Truly these latter immensely complicate the structure of a fuselage subject to great variations of pressure and temperature.

Finally, in east-west flights, the passenger will travel "faster than the sun." Leaving Paris at noon, he will arrive in New York at 10:30 a.m. -- which will require some getting-used-to on the part of the average businessman.

## VII. PILOTING AN S.S.T.

Because of the enormous fuel consumption of the engines, it will be necessary to program the flight exactly in order to carry out the different phases of the flight at optimum altitudes and speeds. A ground-based electronic computer will continuously supply the automatic pilot with data on the basis of fuel consumption, meteorological conditions, and any possible obstacles. The pilot's role will be "reduced" to that of a supervising engineer able to take over the plane in case of emergency should one of the piloting or automatic stabilization devices go bad.

In the same fashion, the plane will be taken in hand by one of the automatic navigation devices on the ground during takeoff and landing since the density of air traffic in 1970 is expected to be several times that of 1960.

## VIII. IS THE SUPERSONIC TRANSPORT TRULY ON HAND FOR TOMORROW?

Opinions on the subject are divided. By way of closing, let us review them:

-- First, the operators, that is, the airline companies, are not at all interested in buying new and very expensive planes before having written off the equally costly jets which have just been put into service. Thus, they do not want delivery of a supersonic transport before 1970. In addition, they demand that this plane be as economical[1] to operate as existing jets and, if possible, safer. Finally, they would like this aircraft to be economical at high subsonic speeds (Mach 0.93, i.e., about 621 m.p.h. -- 1000 km.h.), for medium distances, and for flights above populated regions where the sonic boom might be prohibited.

-- The international organizations for air safety are currently studying the operational problems posed by such craft. They are particularly preoccupied with noise, runway lengths, and the necessary ground control installations. Present experience shows that jet transports came "too soon" and while not themselves completely perfected, they had to

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[1] The economic operation of an airplane is bound up not only with its "technical qualities" but also with the number of actual in-flight hours it can provide each day. The fact of halving the Paris-New York flight time does not mean that the number of flights can be doubled since certain night hours are worth little for the arrival and departure of passengers.

make do with insufficient ground and control facilities. We ought not to fall into the same errors in the next generation. The supersonic transport will not be viable unless it is safer to use than existing planes.

-- The technical people are divided into two frankly opposing camps which defend respectively the "cold" plane (built of light metal and capable of developing speeds up to about Mach 2.2) and the "hot" plane (built of stainless steel and titanium and capable of a progressive development of speeds from Mach 2.5 to Mach 3.5 as technical progress advances).

The first position, flight at Mach 2, is defended by the French (medium-range airliner of about 99 tons (90 metric tons), fig. 21a, carrying 100 passengers for maximum flights of 2670 miles (4300 km.) and English. The Americans prefer the Mach 3 plane (long-range airliner of 198/242 tons (180/200 Metric tons) carrying 120/150 passengers over distances of 4040 miles (6500 km.) or more) and they feel that only a structure resistant to high temperatures would permit a progressive increase in speed (from Mach 2.4 to Mach 3 or more). Putting the stainless steel Mach 3 B-70 Valkyrie bomber into service will enable them to gain incomparable experience, which they will be tempted to use later on for a civil transport more or less derived from it (the transport will have to be much more "sophisticated" to be safe and economically operable). /202

-- Finally, the taxpayer feels that all this is going to cost him a good deal of money. Such an aircraft can not actually be studied without financial aid from governments. Up until now, most commercial aircraft have been able to benefit more or less directly from military orders. This will probably not be the case for the supersonic transport which will have to be uniquely adapted to its civilian mission. However, theoretical experimental and technological research undertaken in the study of an S.S.T. will constitute an indispensable capital for a competitive aeronautical industry.

-- The last argument is of a political (and psychological) nature since there is a definite prestige value to be had by being the first to put such an aircraft on the international market.

For our country, beginning construction of a medium-range supersonic transport must be the logical followup to the success of the Caravelle. Let us hope that it will be the major work, but also the masterwork, of our aircraft industry during the next ten years.

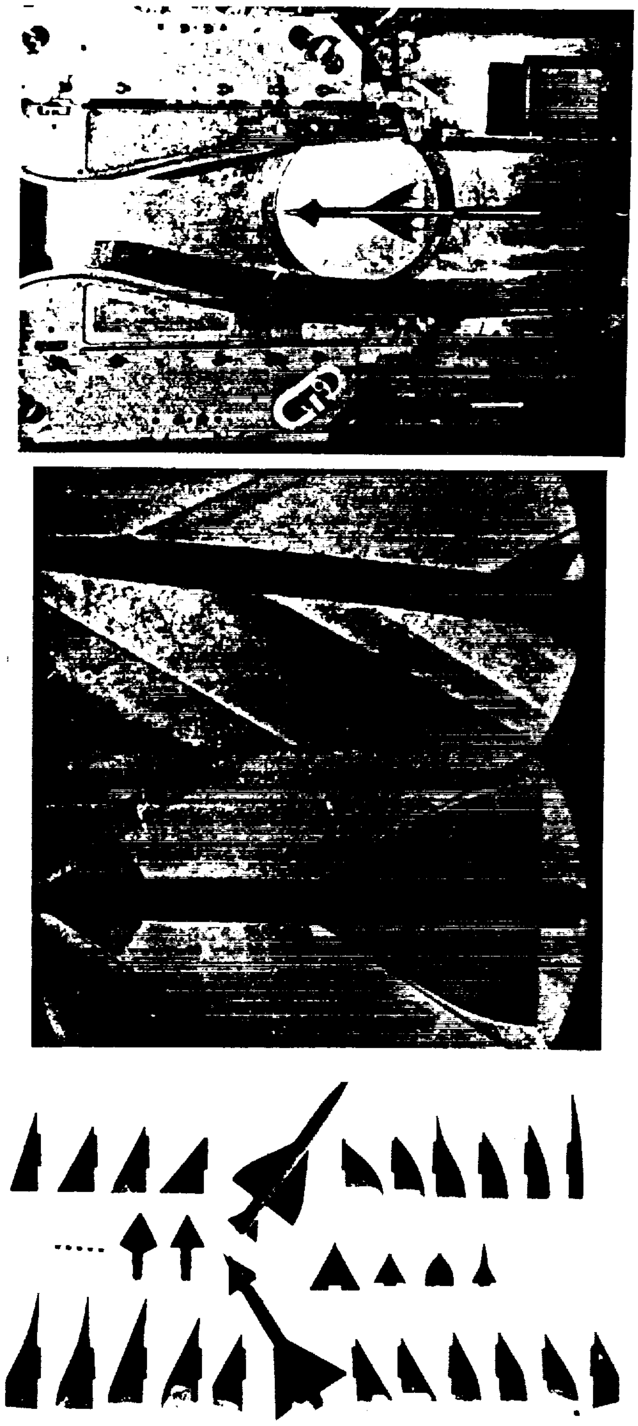


Fig. 7d. Studies of the supersonic transport at O.N.E.R.A.

1) Supersonic wind tunnel S5 at Chalais, Mach 2.1 -- measuring the tendency of a model to sideslip

2) Views showing striation of the airflow at Mach 2.1 on a model with canard stabilizers and double fins

3) Systematic study of wind forms on models at speeds from Mach 0.5 to Mach 3

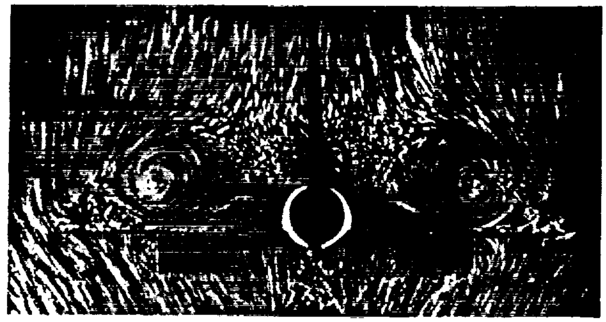


Fig. 17b. Visualization of the vortices at 12° of incidence on the upper surface of the wings of the "Super-Caravelle" in the hydrodynamic tunnel of Châtillon (O.N.E.R.A.)

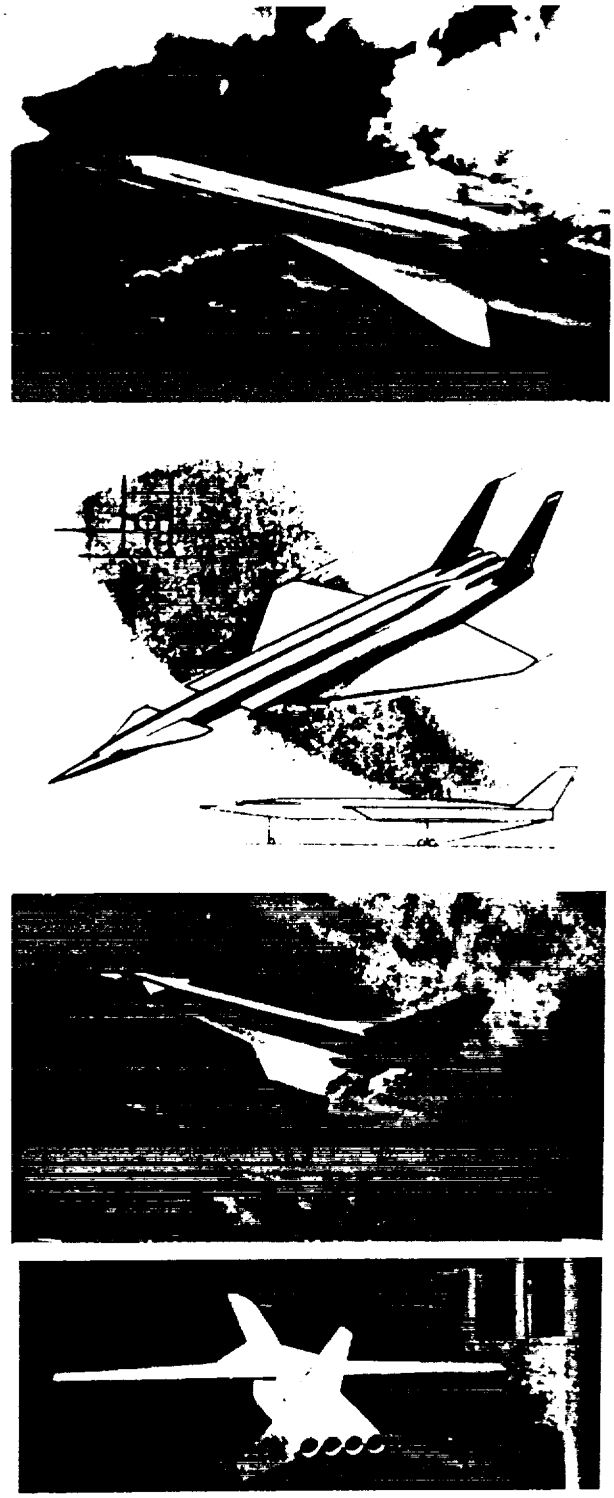
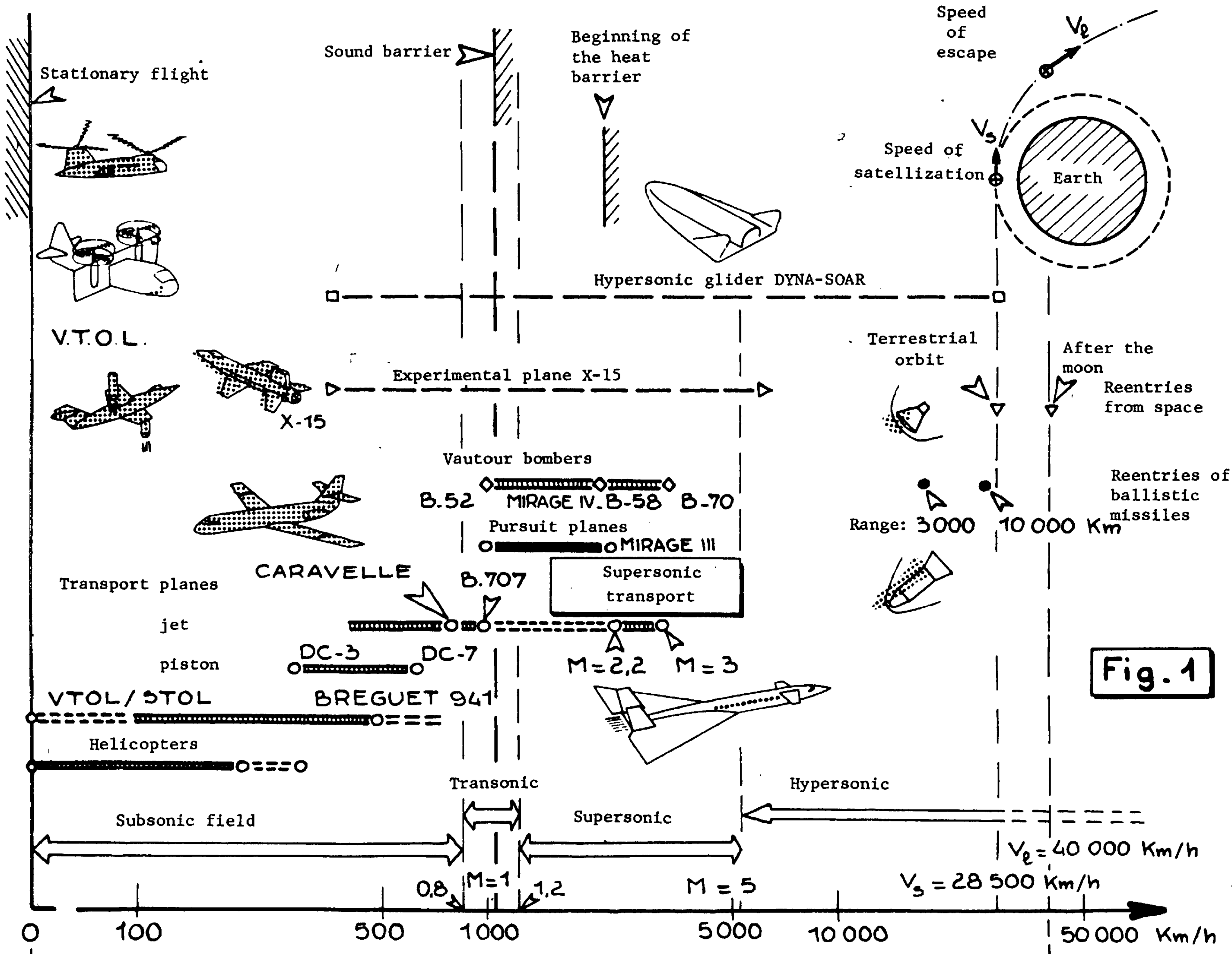


Fig. 21. Plans for supersonic transports

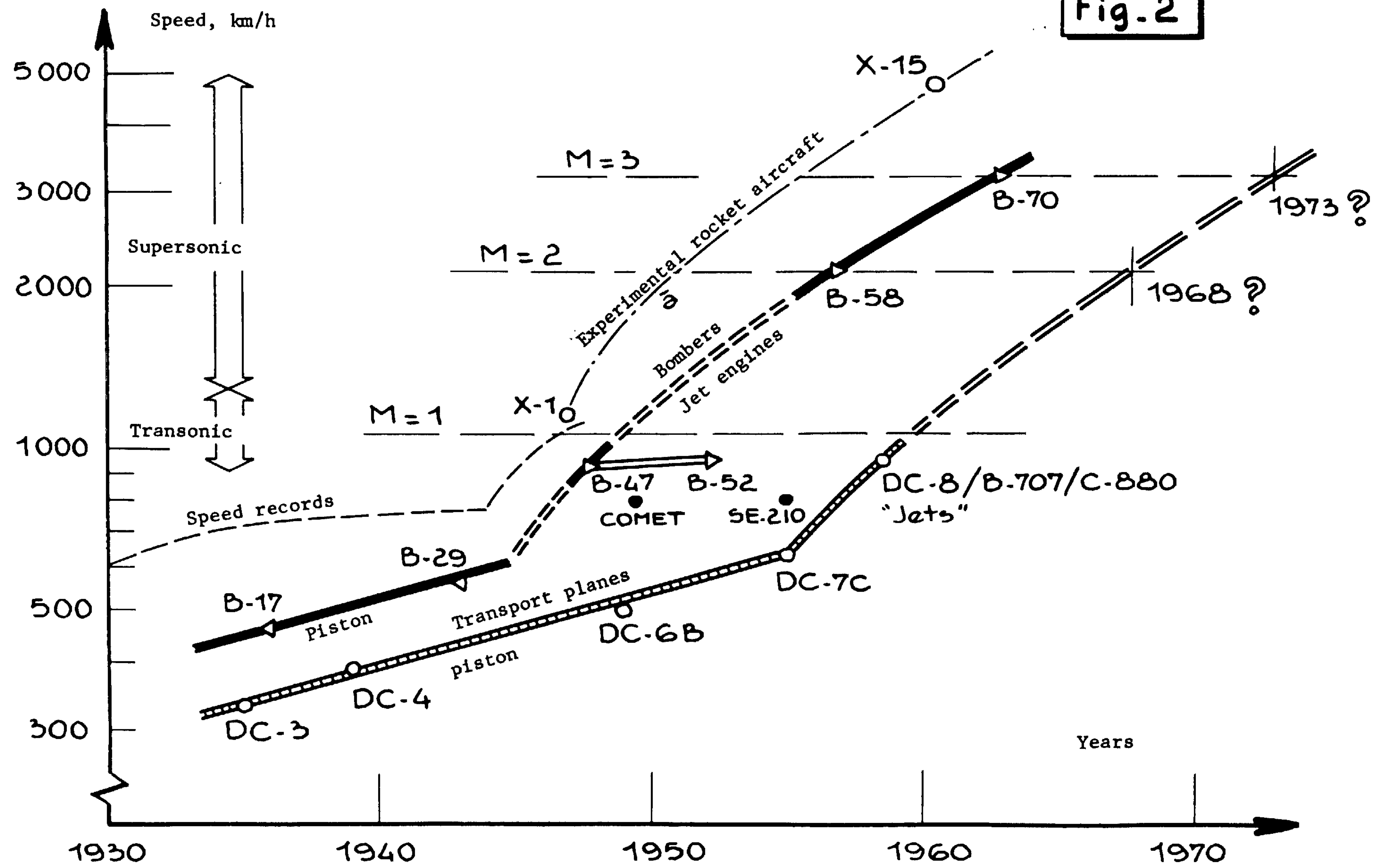
a) Flying wing "Super-Caravelle" by Sud-Aviation and Dassault (Mach 2.2)
b) Advance-model Boeing (Mach 3)
c) Advance-model Douglas (Mach 3)
d) Wind-tunnel study of the variable-geometry wing (N.A.S.A.)



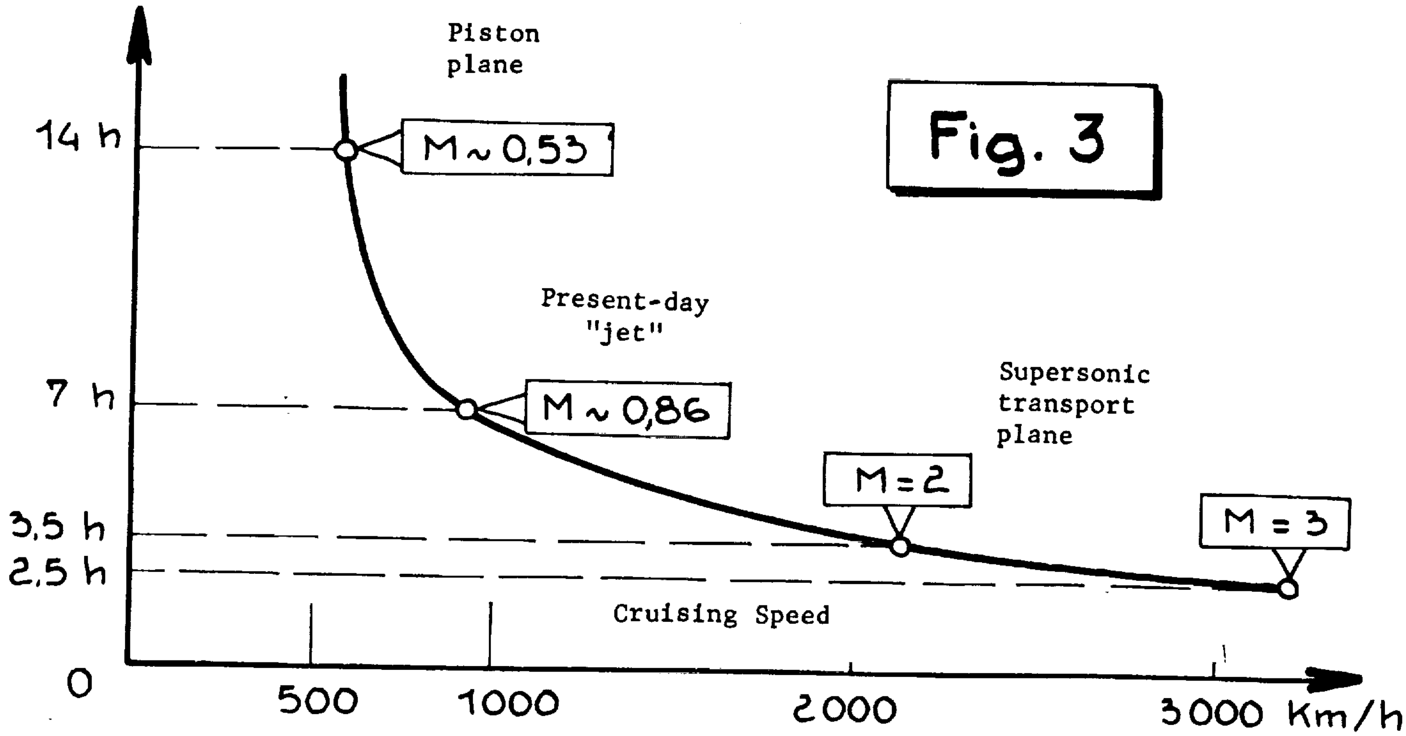
Stationary flight
Sound barrier
Beginning of the heat barrier
Speed of escape
$V_\ell$
$V_s$
Speed of satellization
Earth
V.T.O.L.
Hypersonic glider DYNA-SOAR
Experimental plane X-15
X-15
Terrestrial orbit
After the moon
Reentries from space
Vautour bombers
B.52
MIRAGE IV
B-58
B-70
Pursuit planes
MIRAGE III
Reentries of ballistic missiles
Range: 3000
10 000 Km
Transport planes
CARAVELLE
B.707
Supersonic transport
jet
piston
DC-3
DC-7
M=2,2
M=3
VTOL/STOL
BREGUET 941
Helicopters
Transonic
Hypersonic
Subsonic field
Supersonic
$V_\ell$ = 40 000 Km/h
$V_s$ = 28 500 Km/h
0,8
M=1
1,2
M = 5
0
100
500
1000
5000
10 000
50 000 Km/h


Fig. 1

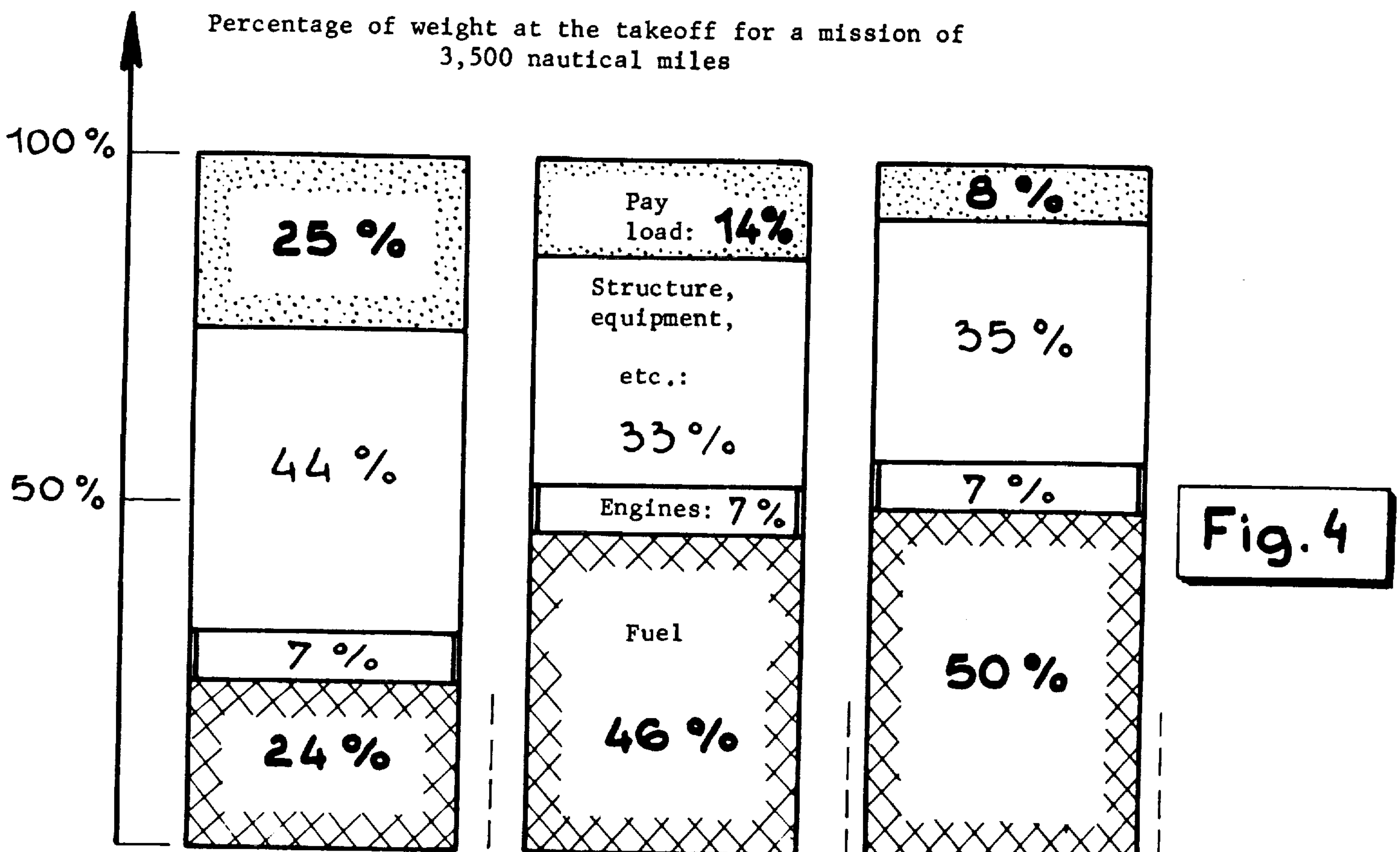
Fig. 2


Speed, km/h
5 000
3 000
2000
1000
500
300
Supersonic
Transonic
Speed records
M = 1
M = 2
M = 3
X-1
X-15
Experimental rocket aircraft
Bombers
Jet engines
B-17
Piston
B-29
B-47
B-52
B-58
B-70
COMET
SE.210
Transport planes
piston
DC-3
DC-4
DC-6B
DC-7C
DC-8/B-707/C-880
"Jets"
1968 ?
1973 ?
Years
1930
1940
1950
1960
1970

Duration of the trip from Paris to New York




Percentage of weight at the takeoff for a mission of 3,500 nautical miles




Turbo-prop. Subsonic "jet" S.T.P. - Weight distribution in long-distance carriers

Dynamic Heating

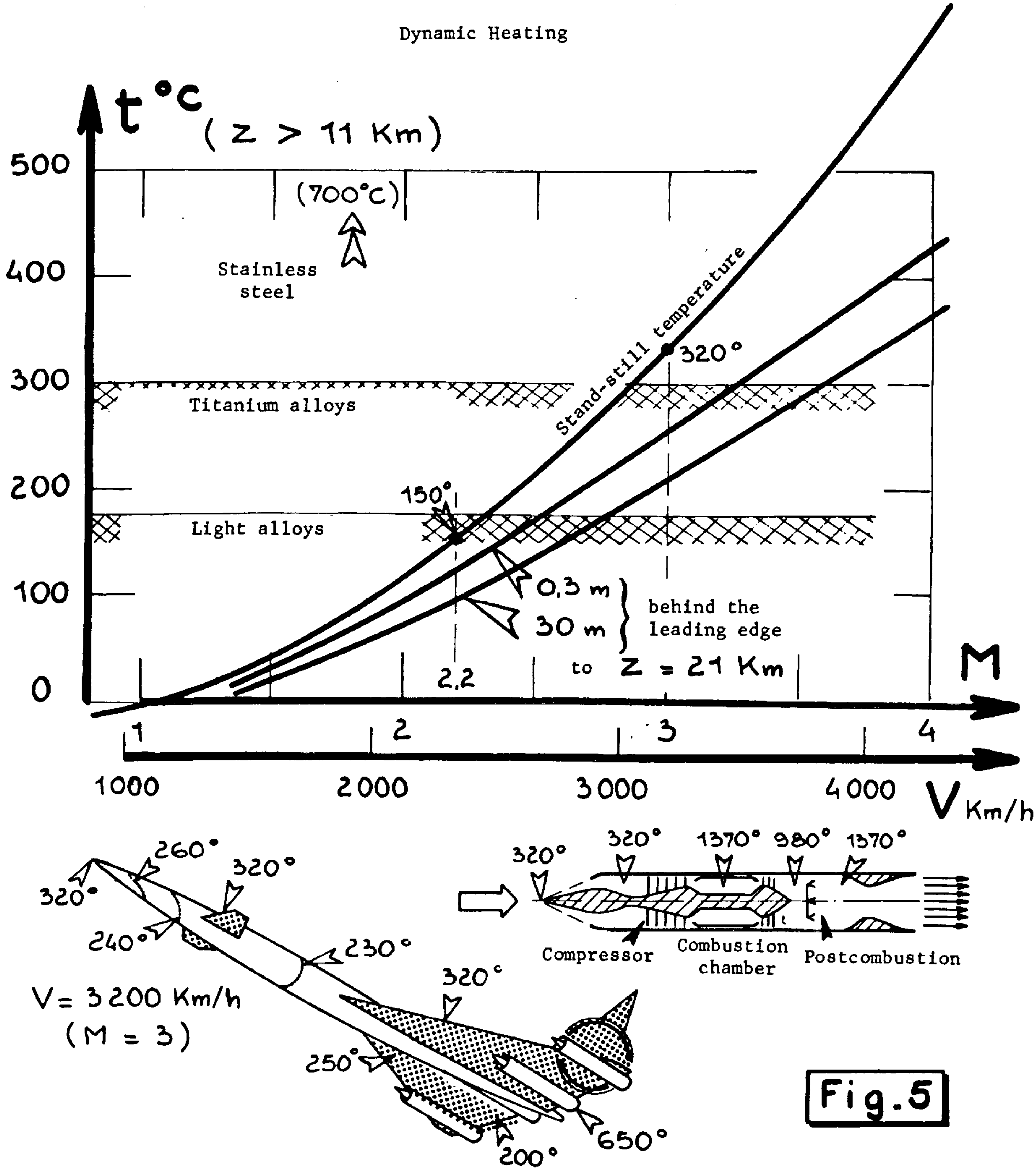
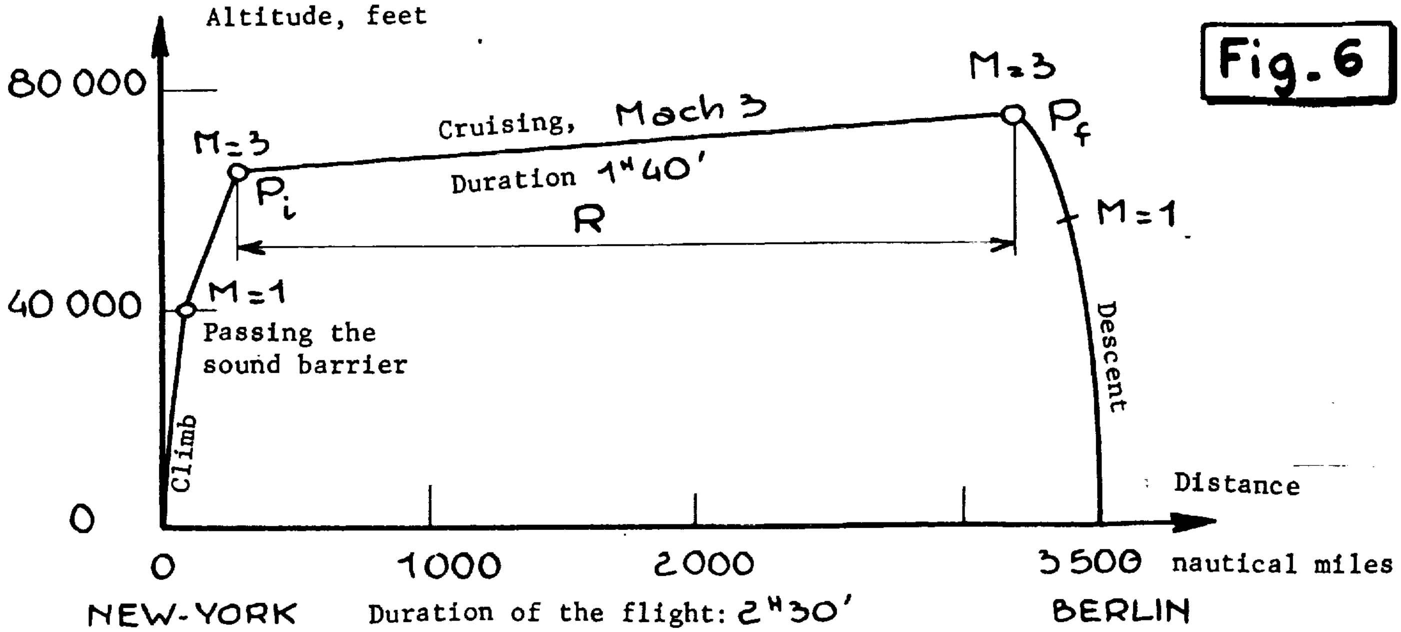



Fig.5

**Fig. 6**




Operating range of a transport plane

Breguet's formula:

$$R = V_0 \times \frac{1}{C_s} \times \left(\frac{C_z}{C_x}\right) \times \mathrm{Log}\left(\frac{P_i}{P_f}\right)$$

$V_0$: Flight speed

$C_s$: Specific consumption of the jet engines

$\frac{C_z}{C_x}$ = $\frac{\text{Lifting capacity}}{\text{Drag}}$ =

$\frac{P_i}{P_f}$: Relation of the weights at the beginning and at the end of cruising $\simeq 1 + \frac{P_{\text{fuel}}}{P_{\text{at empty}}}$

| | | | | |
|---|---|---|---|---|
| $\frac{V_0}{C_s}$ = Thermic yield of the engines | X | Aerodynamic efficiency | X | ~ Structural efficiency |

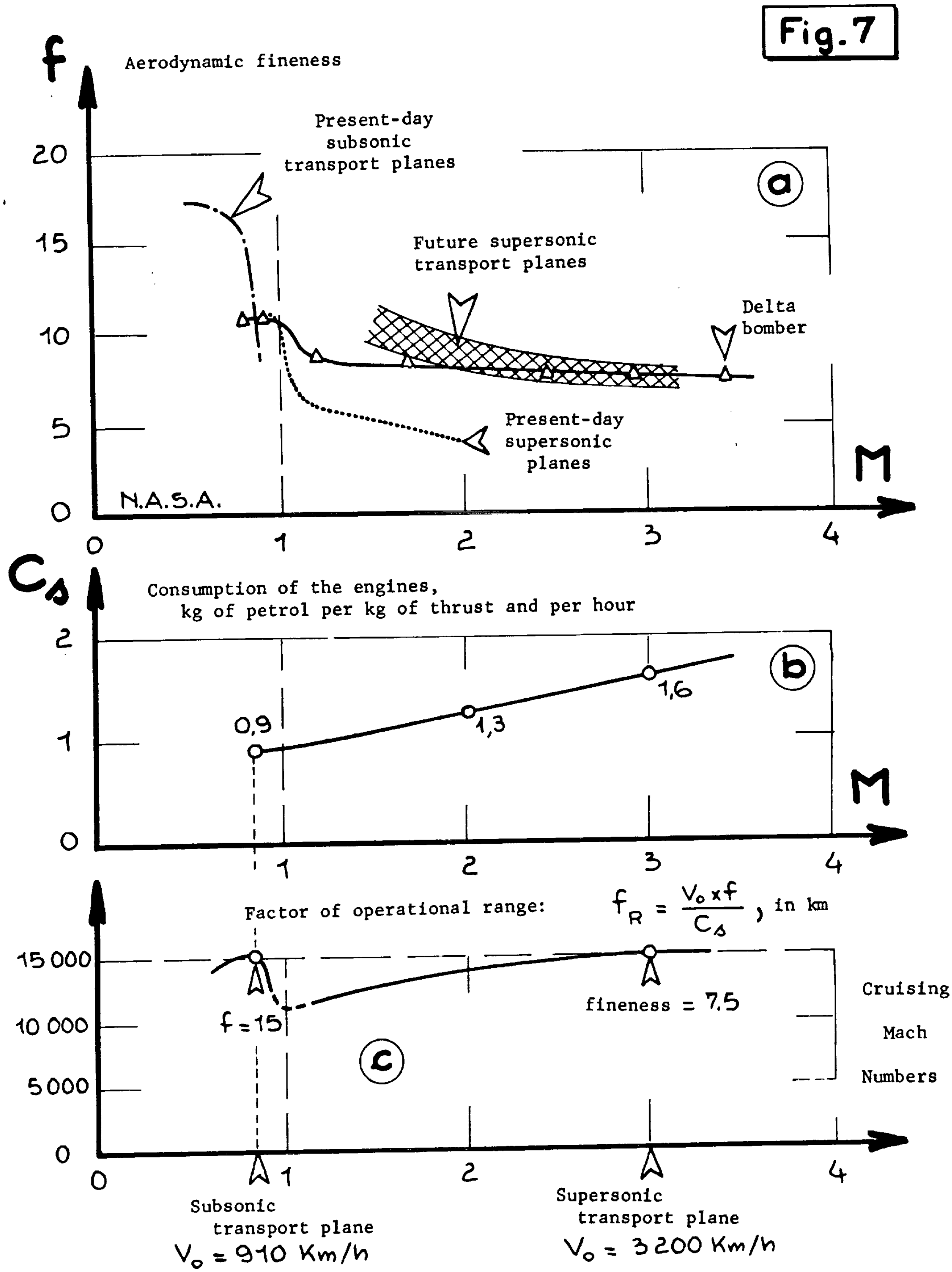


Fig.7
f
Aerodynamic fineness
Present-day subsonic transport planes
Future supersonic transport planes
Delta bomber
Present-day supersonic planes
N.A.S.A.
a
M
20
15
10
5
0
0
1
2
3
4
$C_s$
Consumption of the engines, kg of petrol per kg of thrust and per hour
b
0,9
1,3
1,6
2
1
0
M
Factor of operational range: $f_R = \frac{V_o \times f}{C_s}$, in km
15 000
10 000
5000
0
f = 15
fineness = 7.5
c
Cruising Mach Numbers
Subsonic transport plane
$V_o$ = 910 Km/h
Supersonic transport plane
$V_o$ = 3 200 Km/h

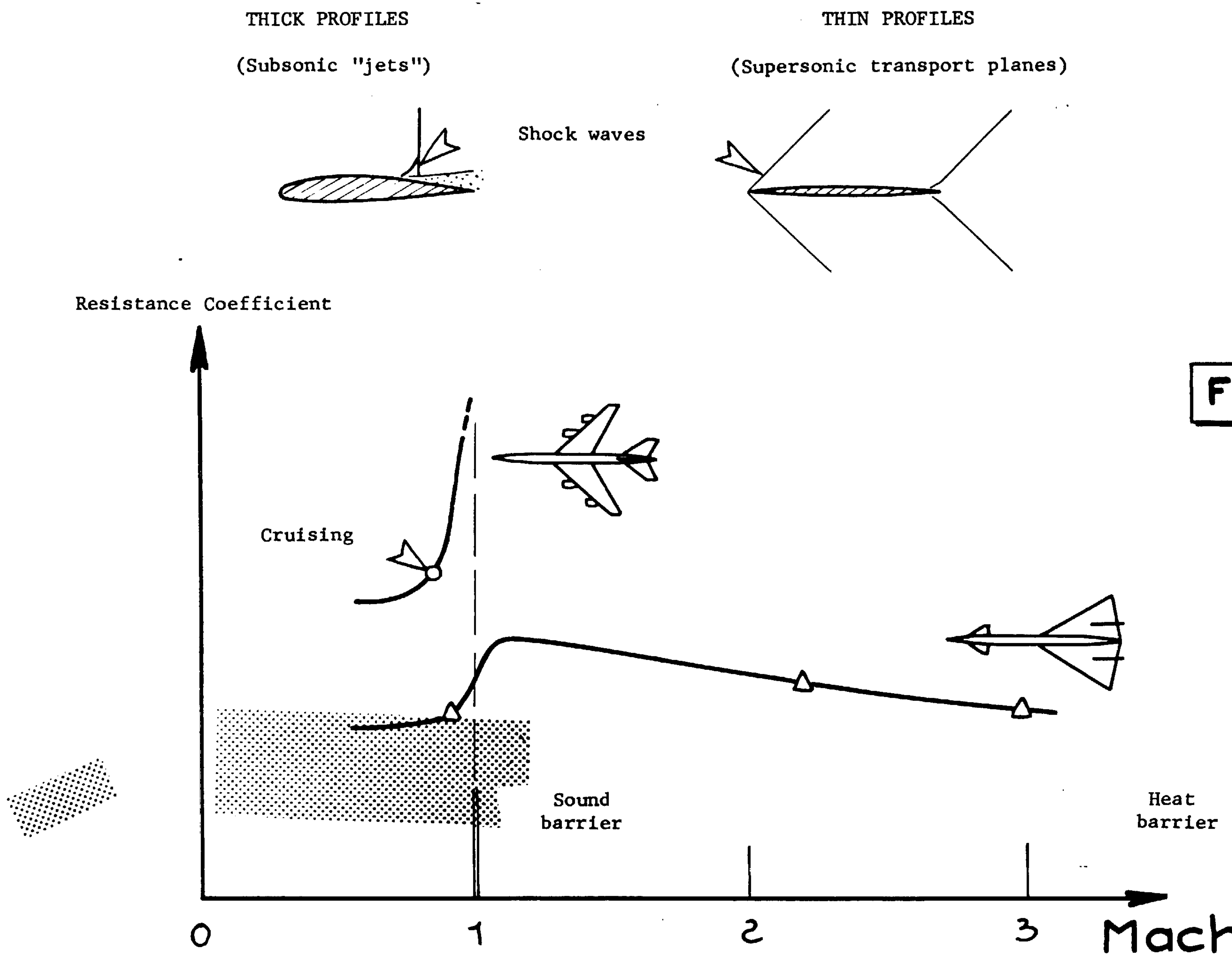

THICK PROFILES
(Subsonic "jets")
Shock waves
THIN PROFILES
(Supersonic transport planes)
Resistance Coefficient
Cruising
Sound
barrier
Heat
barrier
0
1
2
3
Mach

Fig. 8

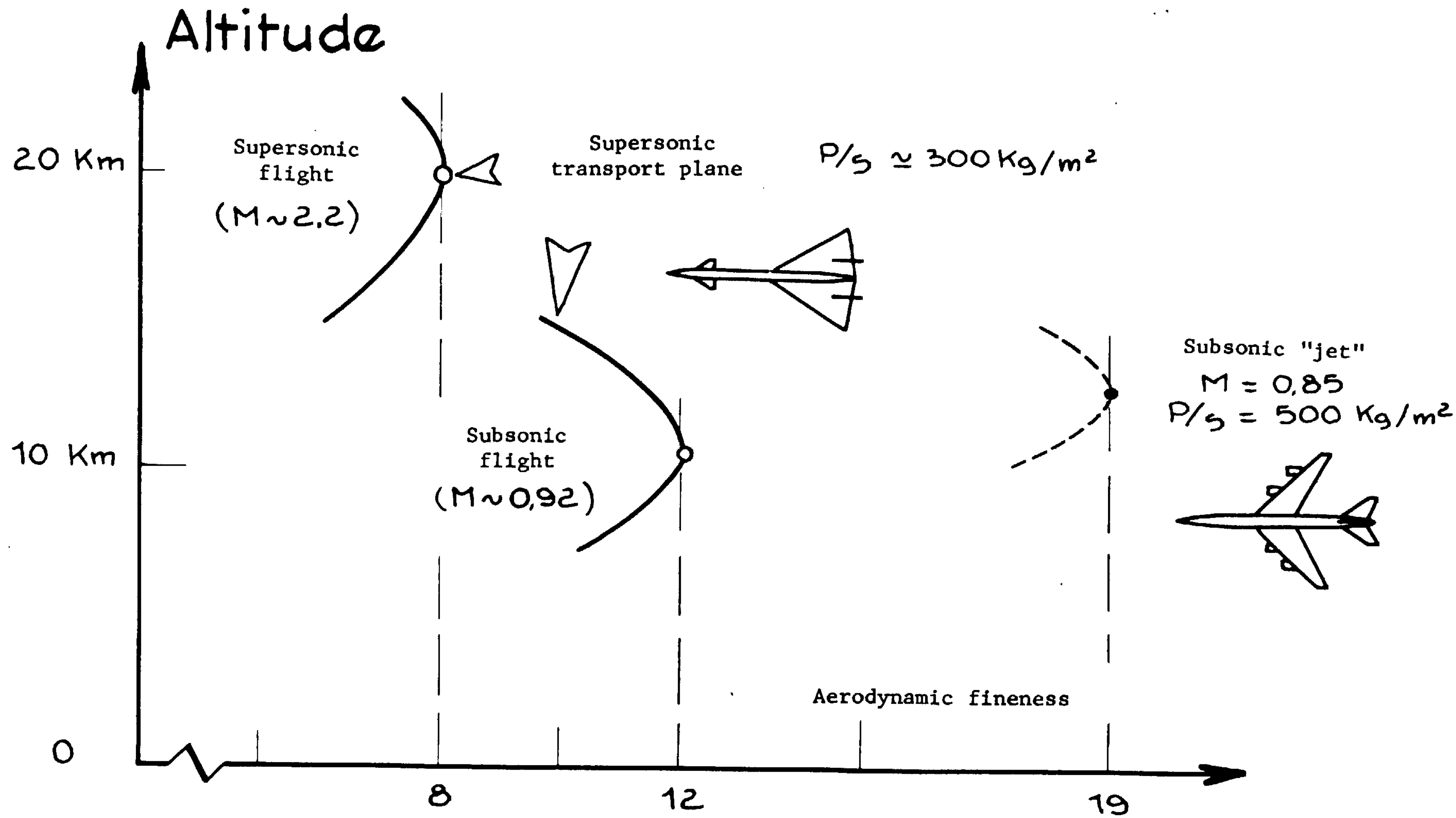



**Fig. 9**

Cruising altitude of the S.T.P.

**Fig.10**

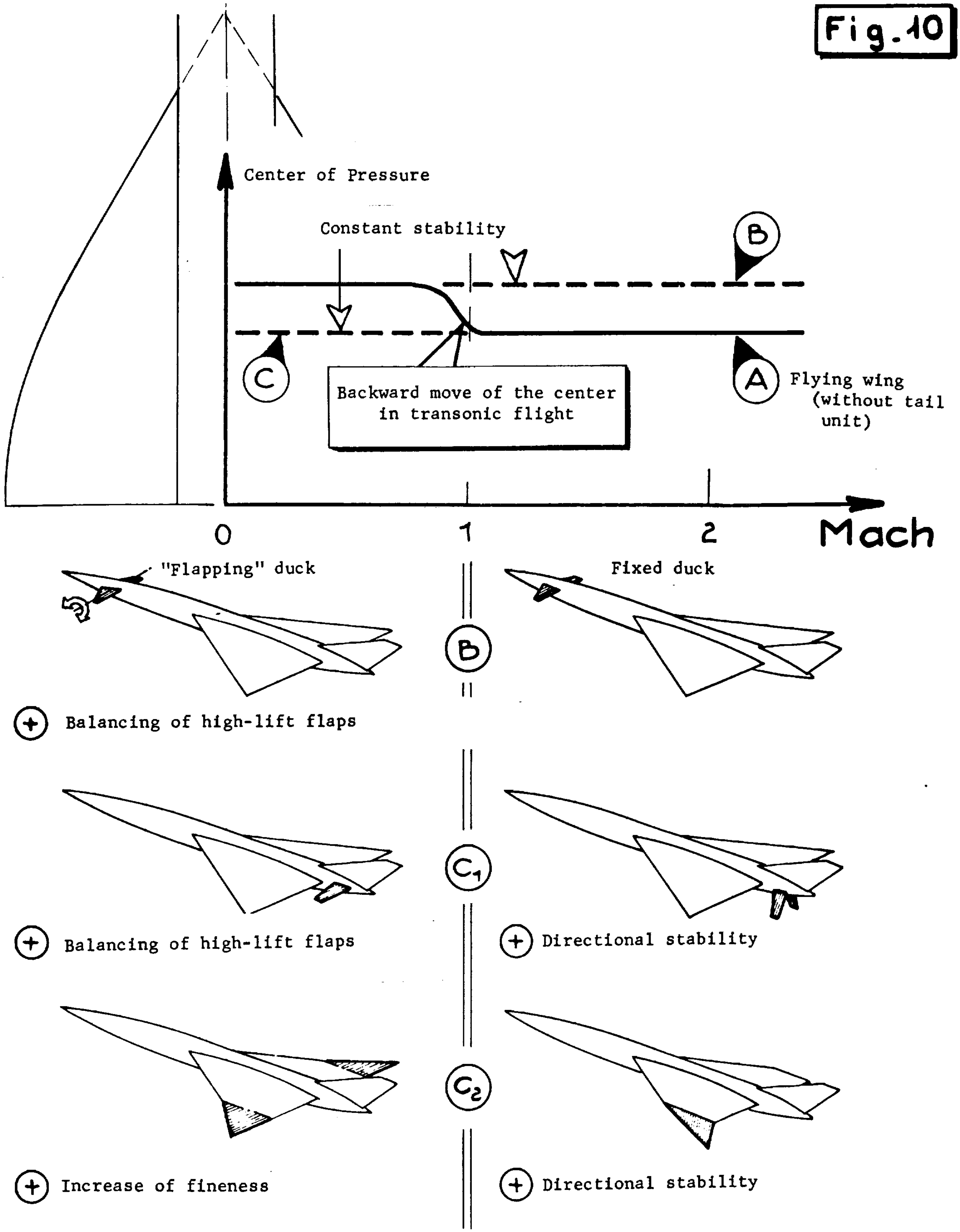
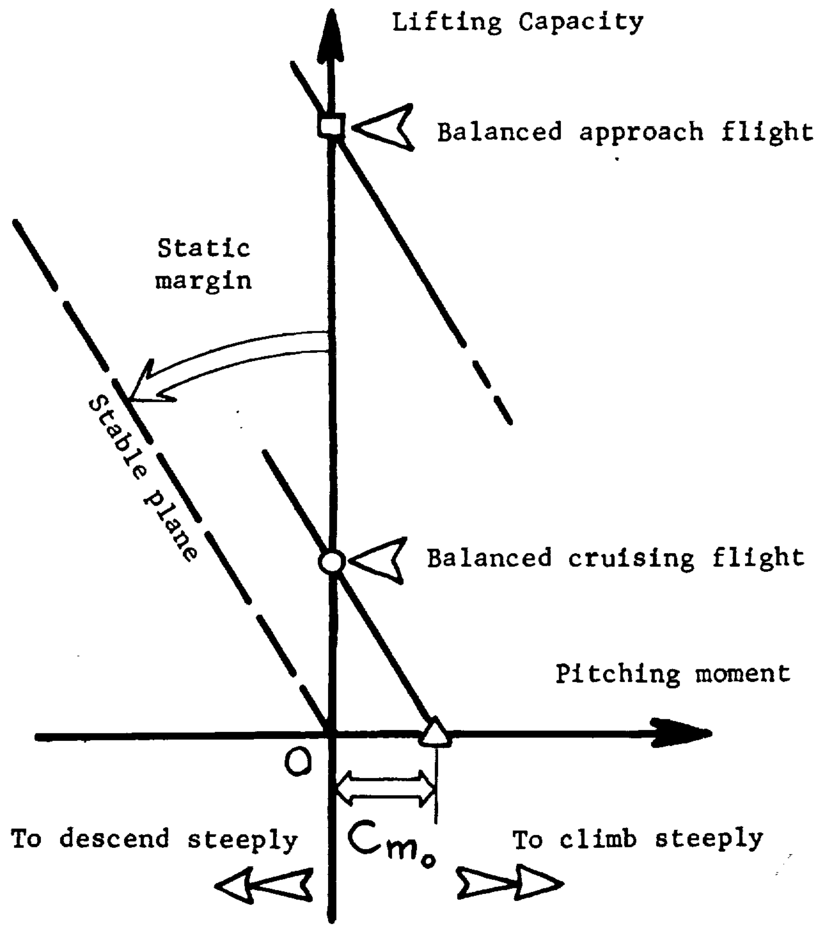
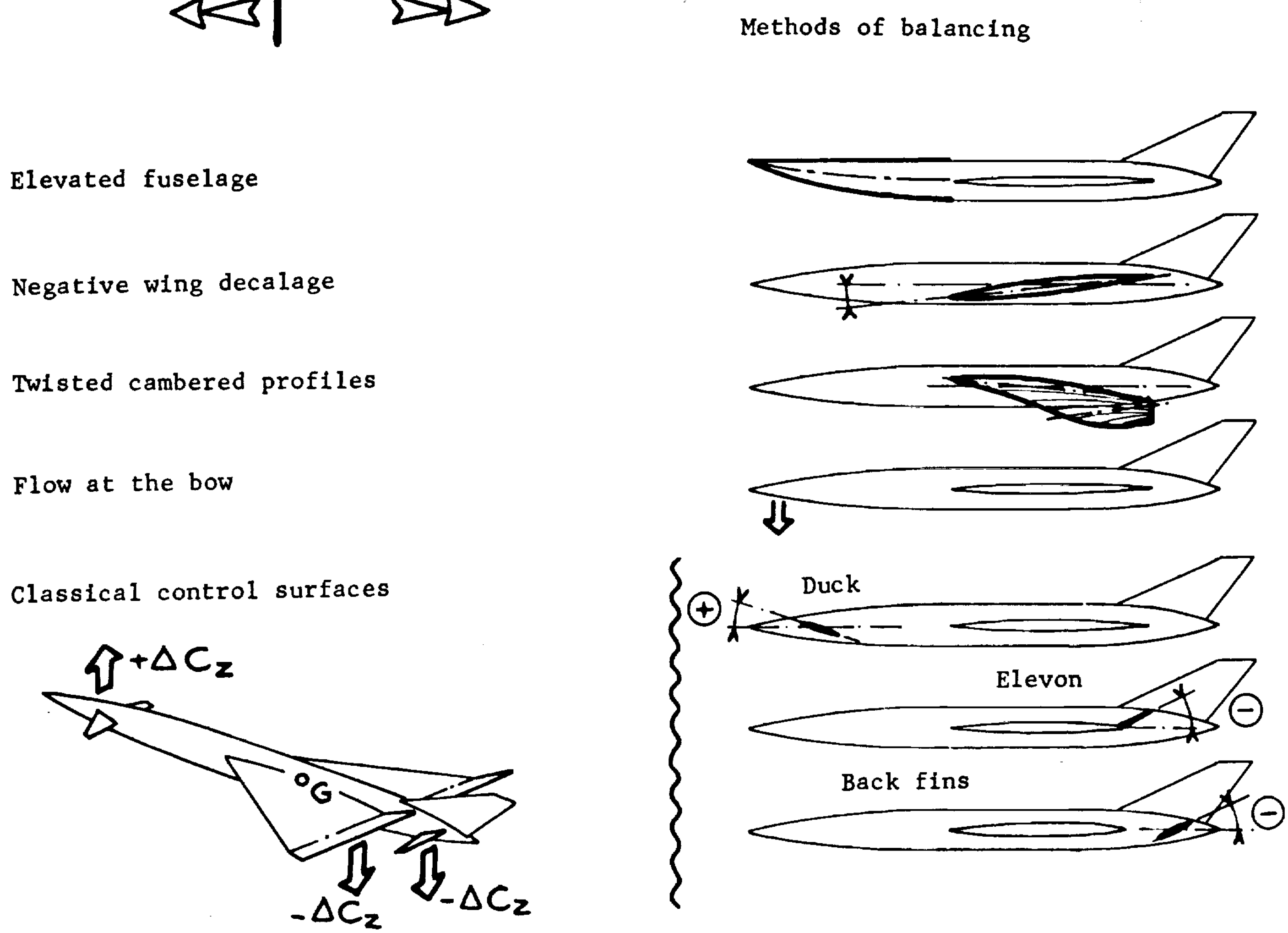

Center of Pressure
Constant stability
B
C
A
Backward move of the center in transonic flight
Flying wing (without tail unit)
0
1
2
Mach
"Flapping" duck
Fixed duck
B
+ Balancing of high-lift flaps
C1
+ Balancing of high-lift flaps
+ Directional stability
C2
+ Increase of fineness
+ Directional stability

Fig. 11


Lifting Capacity
Balanced approach flight
Static
margin
Stable plane
Balanced cruising flight
Pitching moment
O
$C_{m_o}$
To descend steeply
To climb steeply


Methods of balancing
Elevated fuselage
Negative wing decalage
Twisted cambered profiles
Flow at the bow
Classical control surfaces
$+\Delta C_z$
G
$-\Delta C_z$
$-\Delta C_z$
Duck
Elevon
Back fins

Resistance balance during supersonic cruising



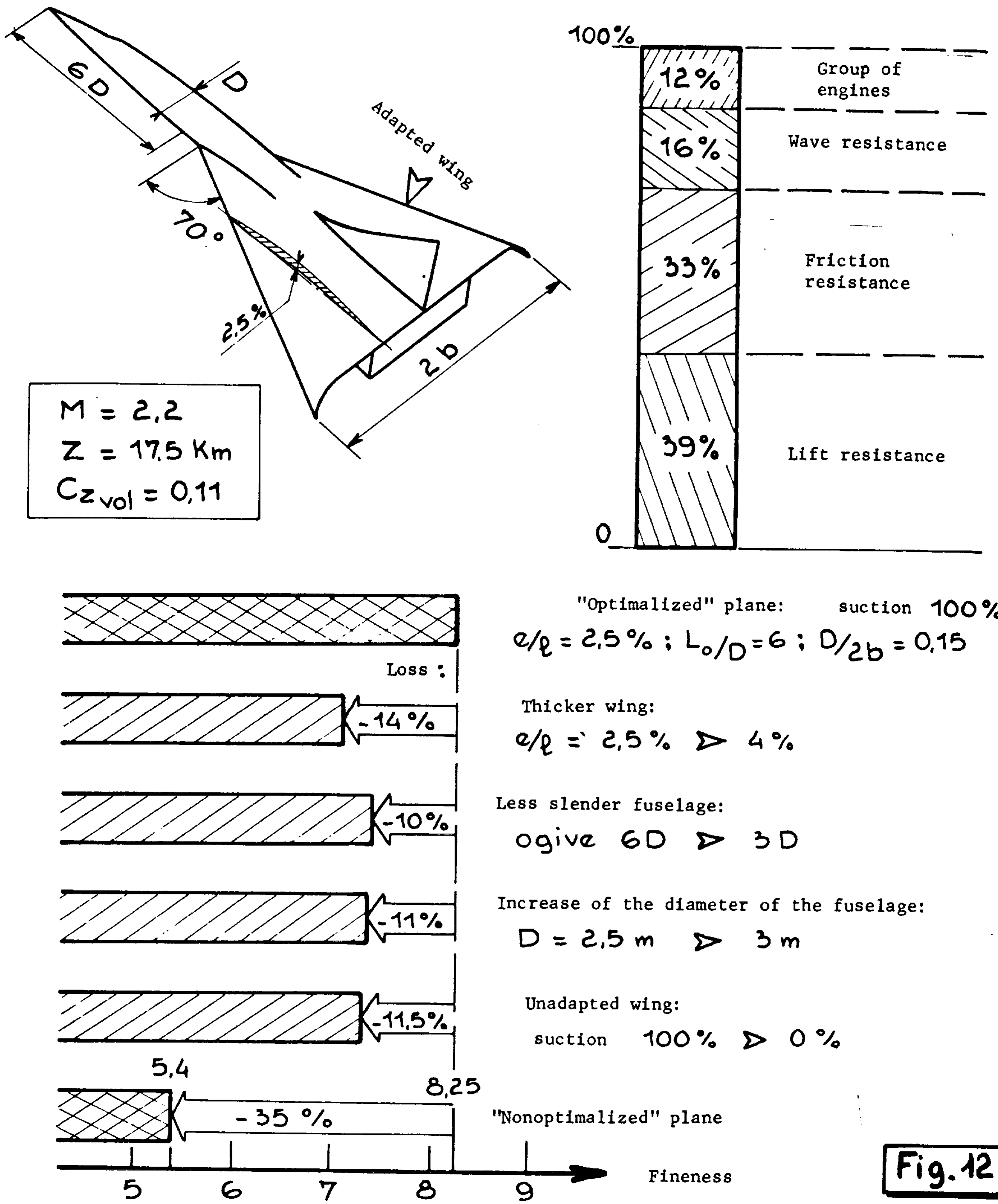



Fig. 12

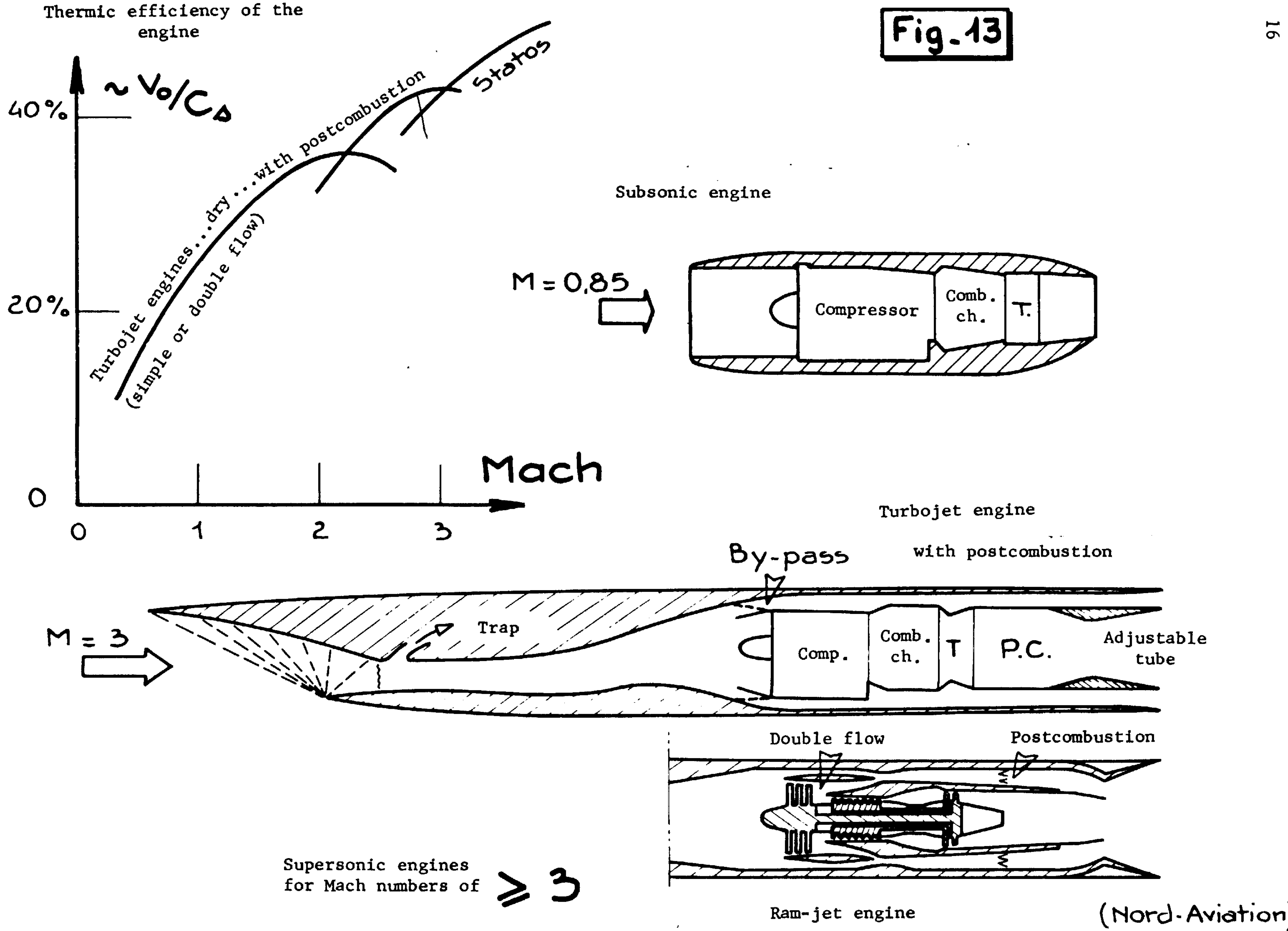

Thermic efficiency of the engine
~ Vo/Ca
40%
20%
0
Turbojet engines...dry...with postcombustion
(simple or double flow)
Statos
Mach
0
1
2
3
Subsonic engine
M = 0,85
Compressor
Comb. ch.
T.
Turbojet engine with postcombustion
By-pass
M = 3
Trap
Comp.
Comb. ch.
T
P.C.
Adjustable tube
Double flow
Postcombustion
Supersonic engines for Mach numbers of ≥ 3
Ram-jet engine
(Nord-Aviation)

Fig. 13

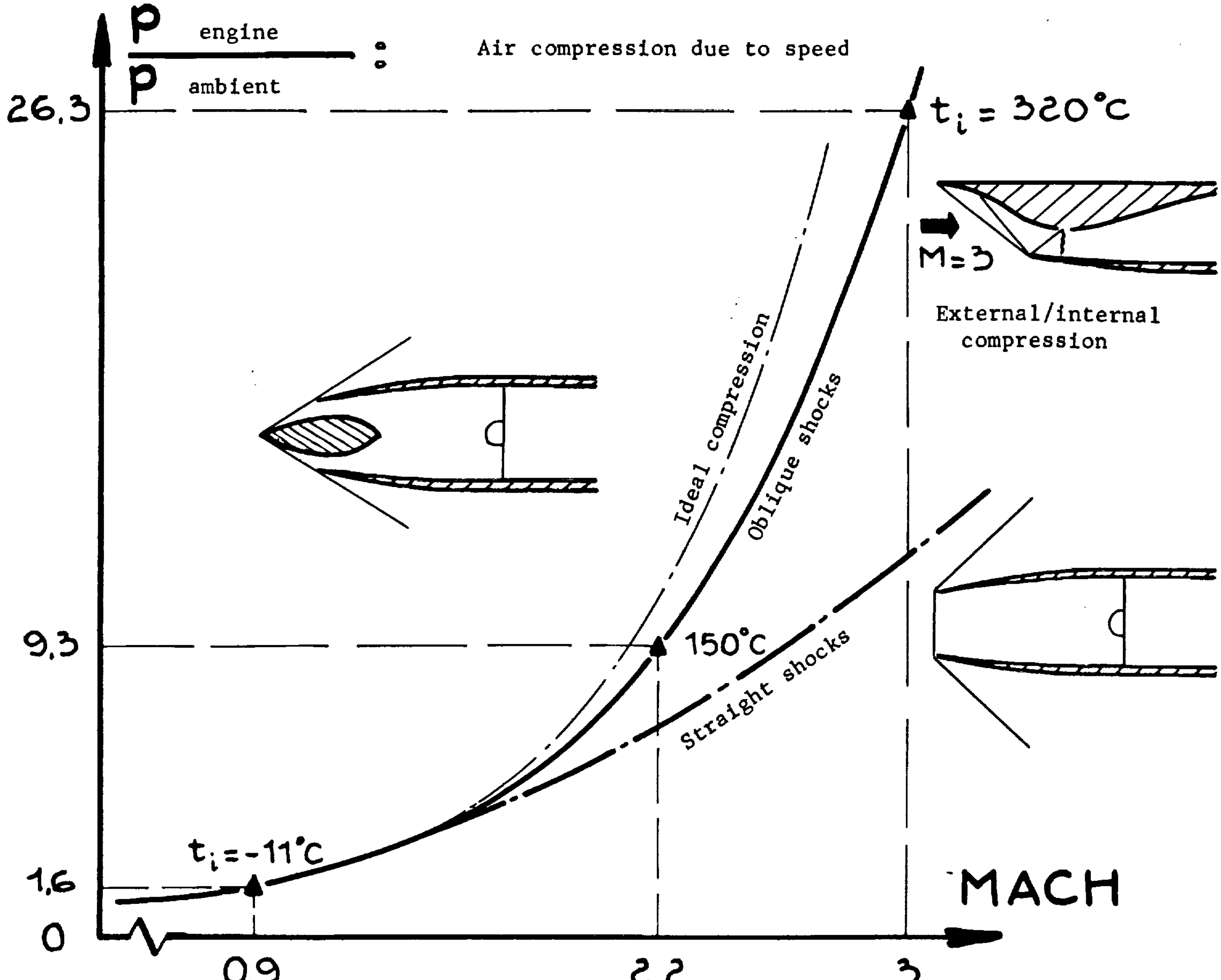
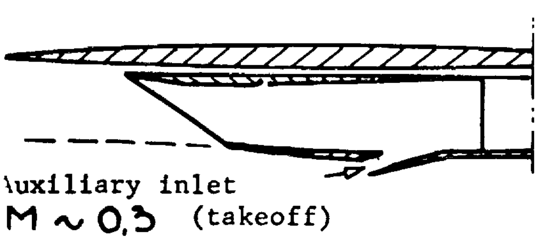
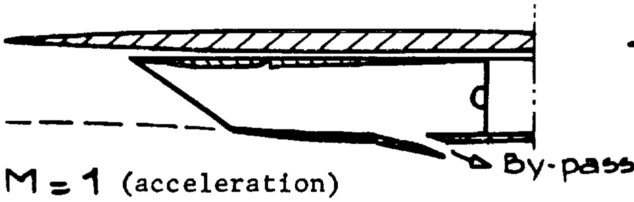
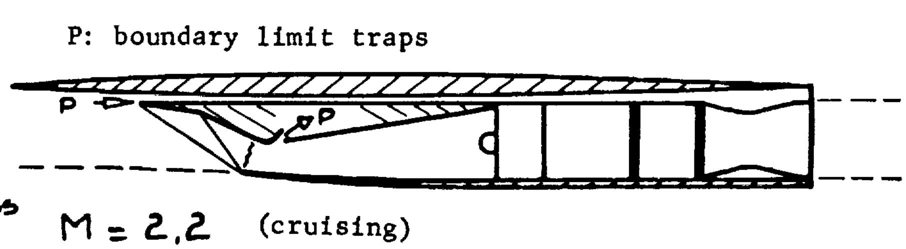



Fig.14

Two-dimensional air intake
in the case of variable
geometry
(compression by two
oblique external shocks)



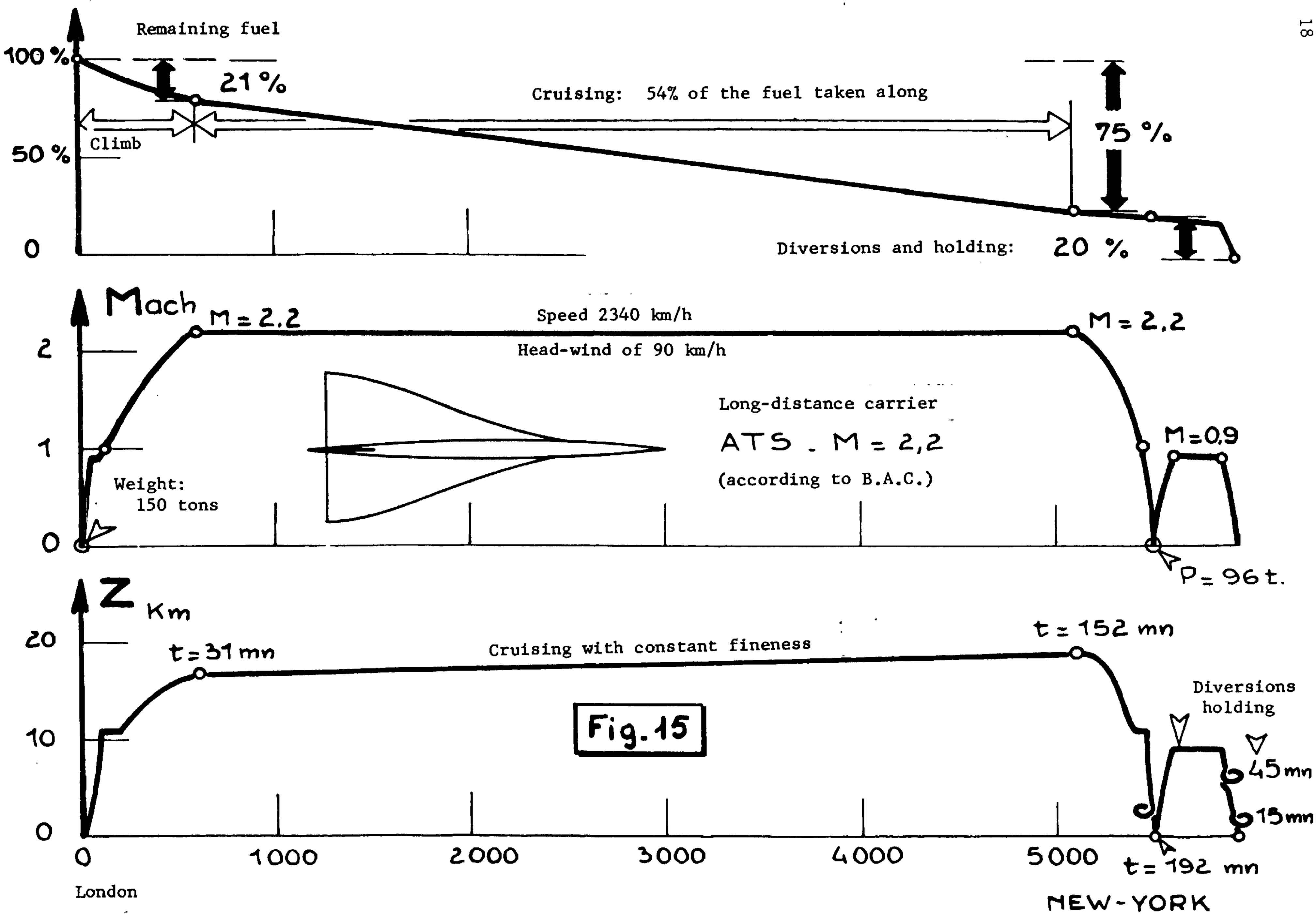
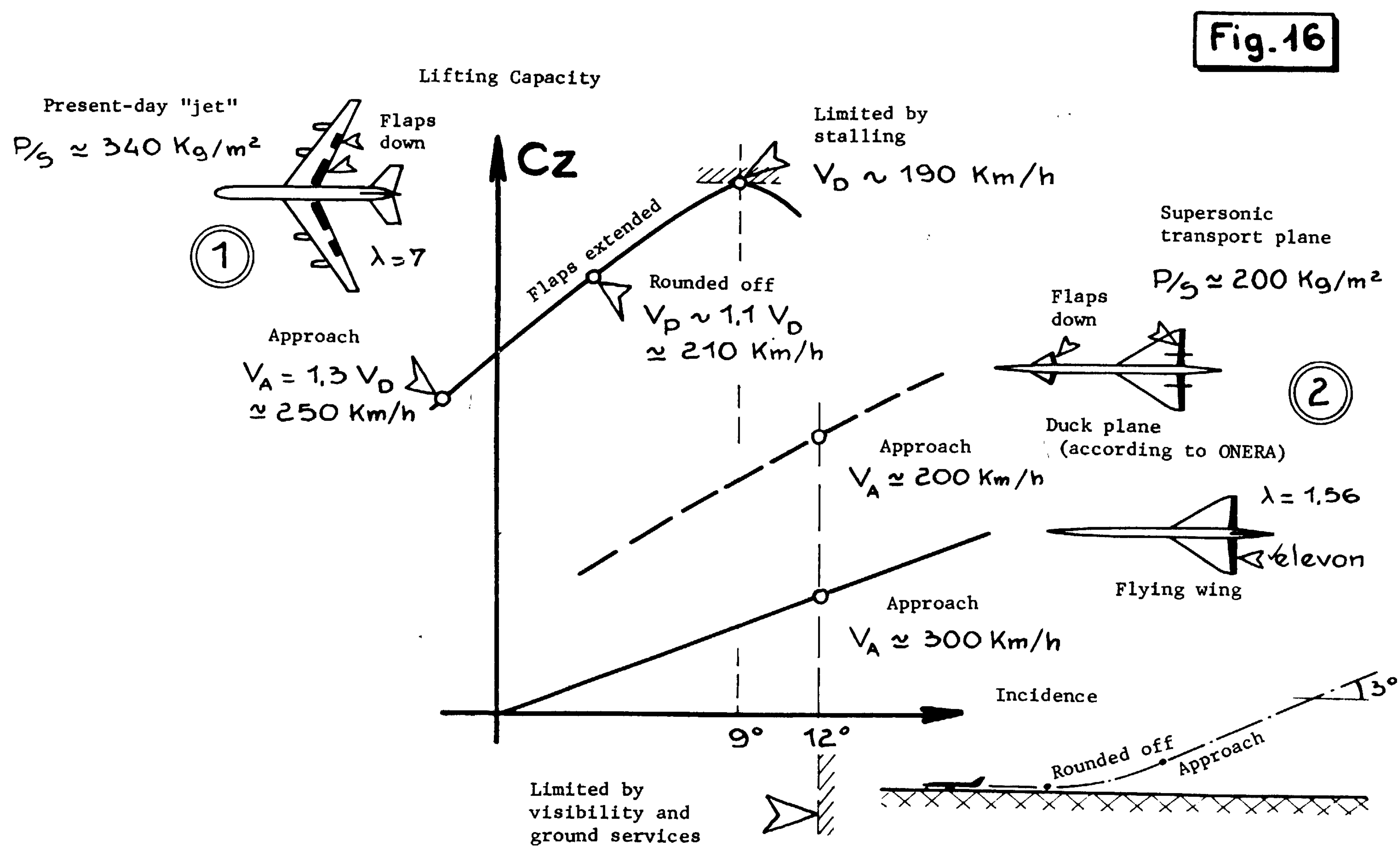
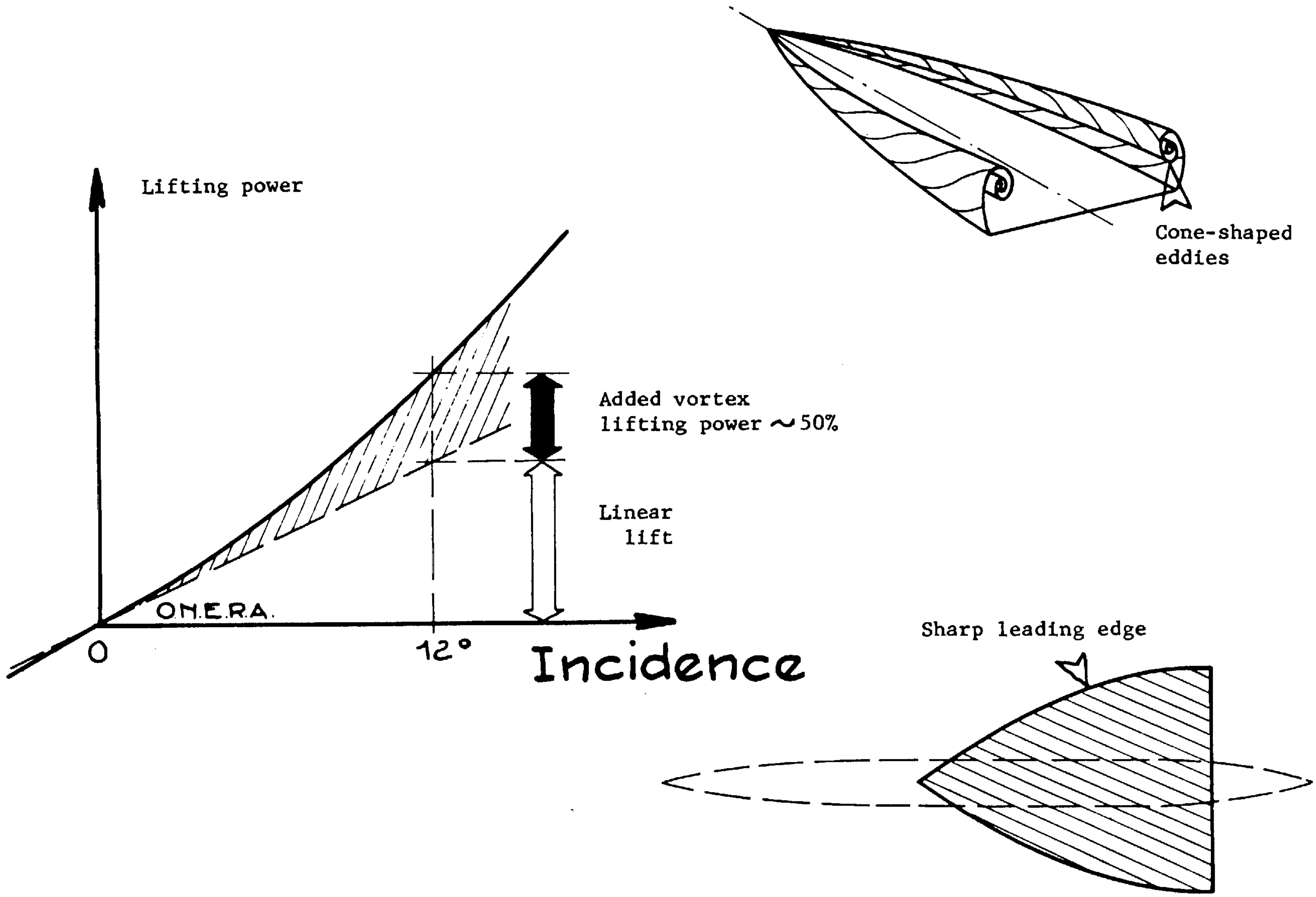

Remaining fuel
100 %
50 %
0
21 %
Climb
Cruising: 54% of the fuel taken along
75 %
Diversions and holding: 20 %
Mach
M = 2.2
Speed 2340 km/h
Head-wind of 90 km/h
M = 2.2
2
1
0
Weight:
150 tons
Long-distance carrier
ATS . M = 2,2
(according to B.A.C.)
M=0.9
P = 96 t.
Z Km
20
10
0
t=31 mn
Cruising with constant fineness
t = 152 mn
Diversions
holding
45 mn
15 mn
0
1000
2000
3000
4000
5000
t = 192 mn
London
NEW-YORK

Fig. 15




Approach speeds of jet engine planes

Fig.17a




Gothic wings

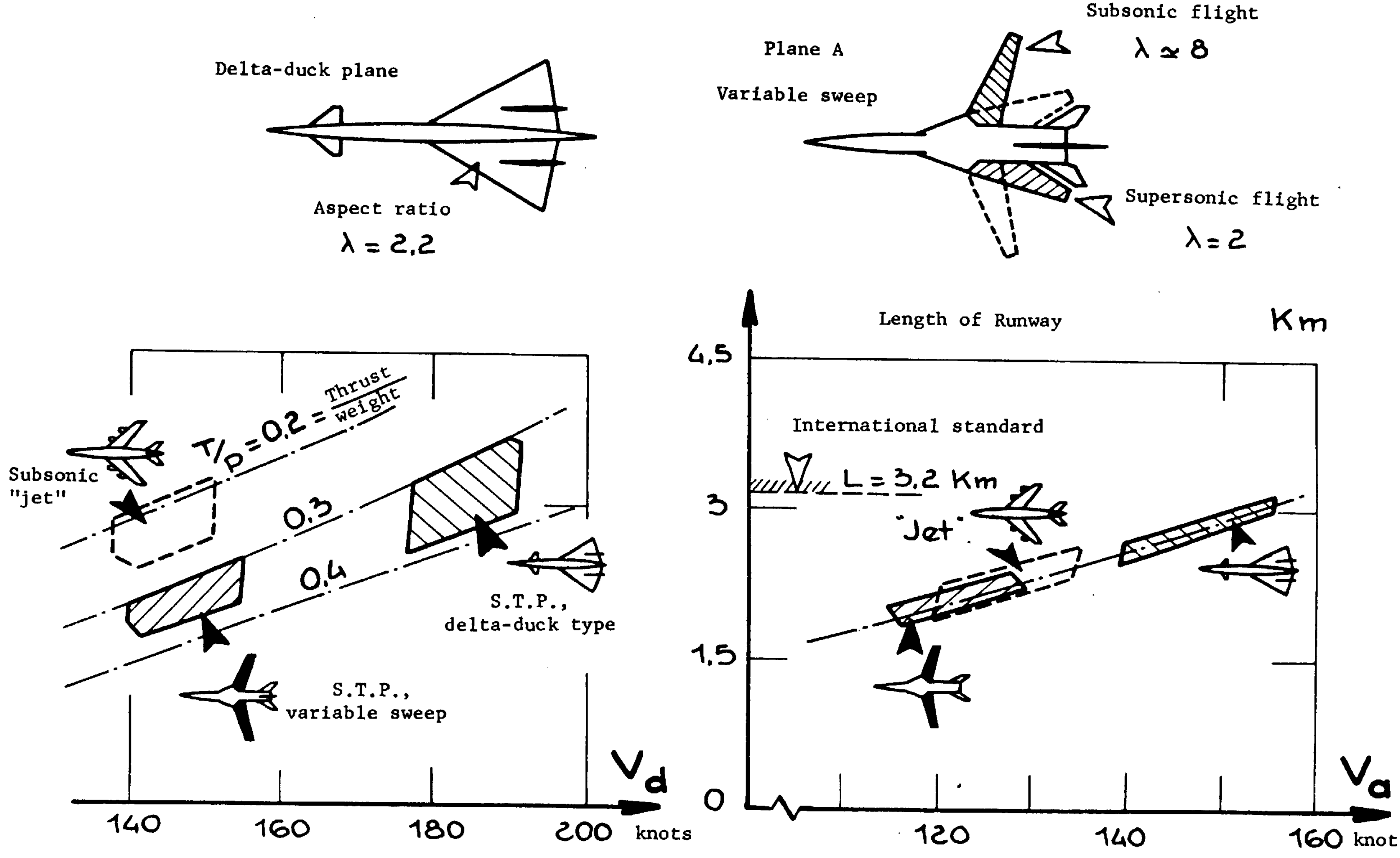



Fig.18

Speeds at takeoff and landing of the Supersonic Transport Plane

according to NASA

S.T.P. at variable sweep

(NASA)

- takeoff
- climbing
- subsonic cruising
- holding and diversions
- landing

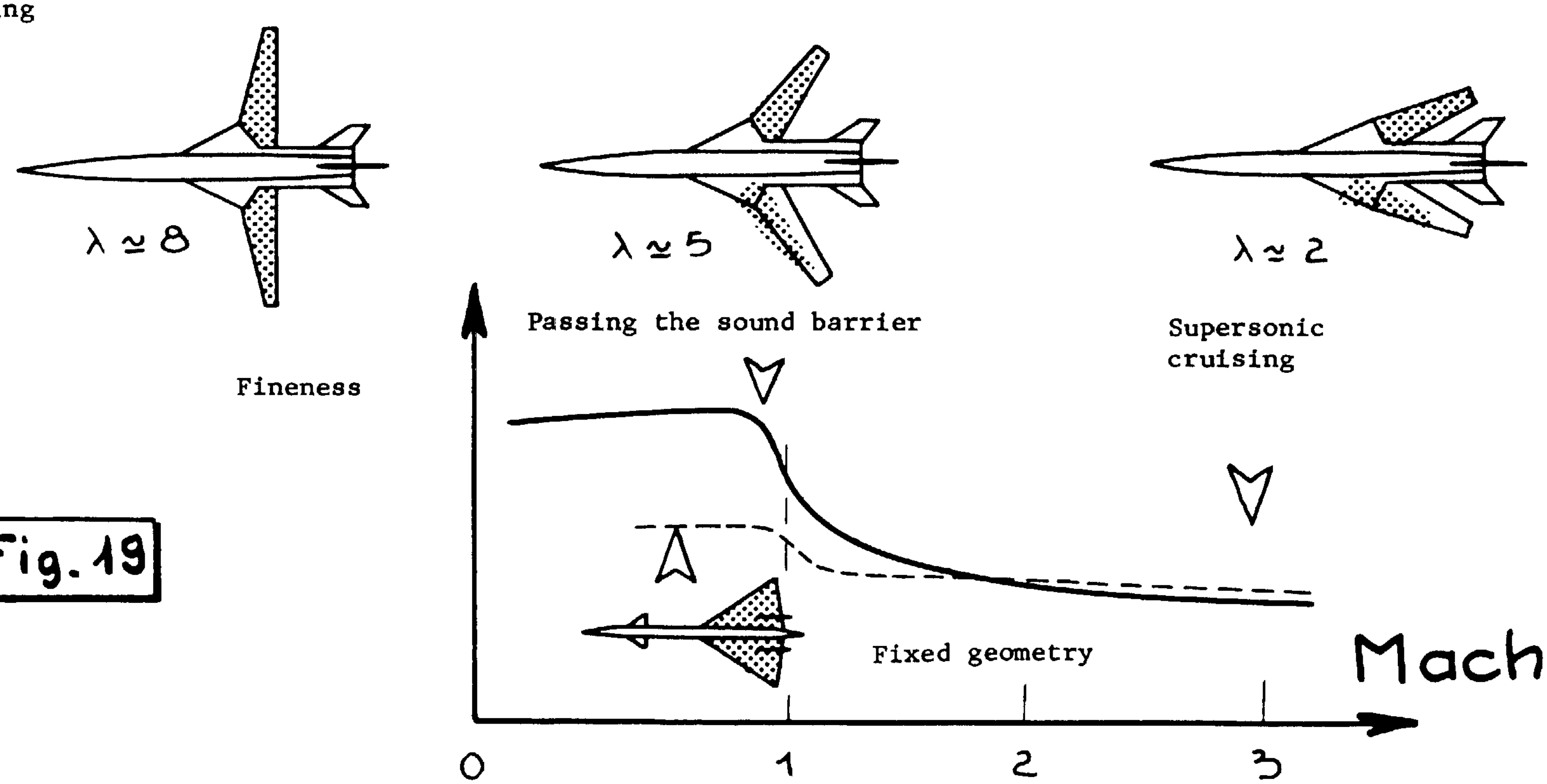
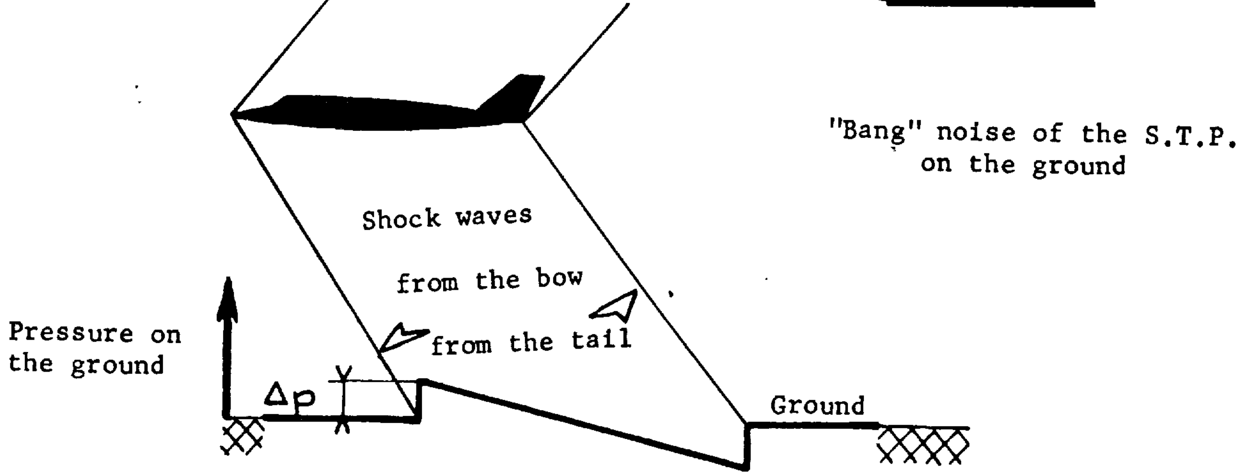



Fig. 19

Fig. 20


"Bang" noise of the S.T.P. on the ground
Shock waves
from the bow
from the tail
Pressure on the ground
Δp
Ground

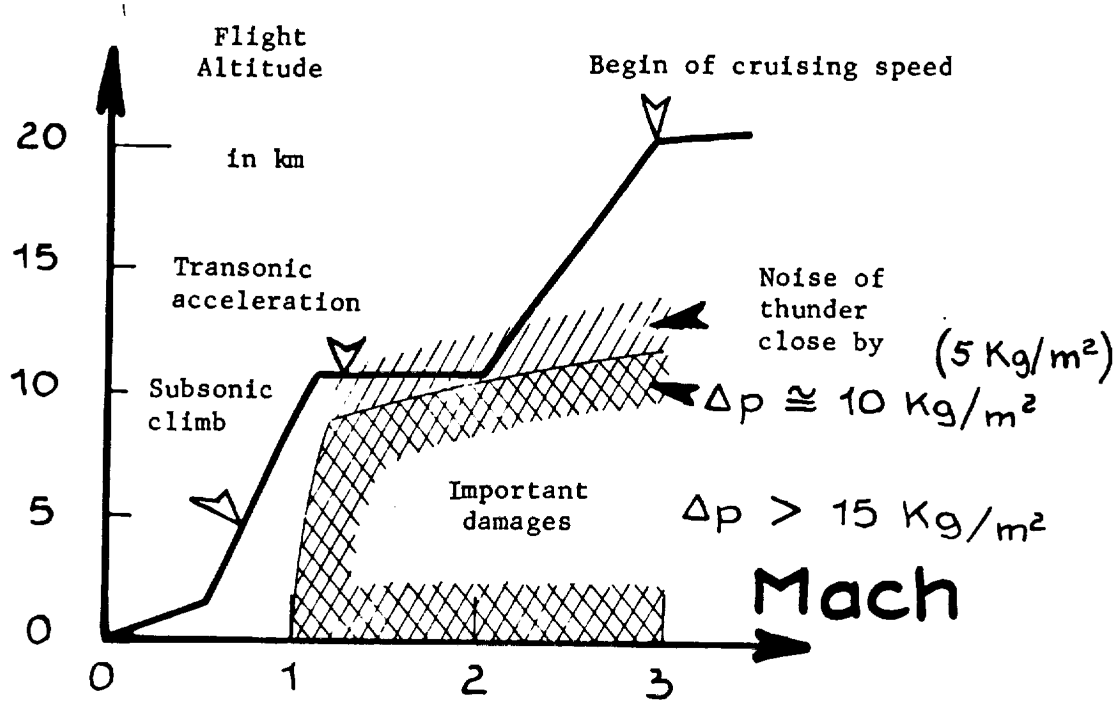

Flight Altitude
in km
Begin of cruising speed
20
15
10
5
0
Transonic acceleration
Subsonic climb
Noise of thunder close by
(5 Kg/m²)
Δp ≅ 10 Kg/m²
Important damages
Δp > 15 Kg/m²
Mach
0
1
2
3

Fig. 1 Localization of the flight field of the supersonic transport plane (S.T.P.) within the range of velocities achieved by man.

Fig. 2 Chronological evolution of the velocity for experimental planes, bombers, and civil transport planes.

Fig. 3 Duration of the trip, Paris to New York, with long-range piston planes, with present-day jet planes, and with the S.T.P. at Mach numbers of 2 and 3.

Fig. 4 Weight relations of the three types of long-distance carriers which show the gradual increase of the fuel consumption and the proportionate decrease of the payload; consequently, the increase of the tonnage of the plane with the flight velocity, for a given number of passengers.

Fig. 5 The heating of the walls of the plane at supersonic speeds; light alloys will have to be given up, above a Mach number of 2.2, approximately, in favor of titanium and stainless steel hulls.

Fig. 6 The factors affecting the operating range of a long-distance plane.

Fig. 7 The effect of the Mach number on the aerodynamic fineness, on the consumption of the engines, and on the operating-range factor (i.e., on the flight performance); this factor decreases, most unfortunately, in the transonic field, once more to reach values that are comparable to those of today's jets, between the Mach numbers of 2 and 3.

Fig. 8 Resistance to advance as a function of the Mach number: the present-day "jet" can not go past the sound barrier, while the S.T.P. is able easily to pass through the transonic field, thanks to its slender forms.

Fig. 9 Optimal flight altitude (at maximum fineness) for a subsonic "jet" and for the S.T.P. (used either as a supersonic or as a subsonic plane); the S.T.P. must fly at supersonic speed at altitudes that are approximately twice as high as those maintained at subsonic speed.

Fig. 10 The stability of a plane increases considerably when it goes beyond the speed of sound; consequently, a supplementary resistance results to balance it during the cruising flight at supersonic speed; several solutions which, at the same time, may improve other flight characteristics, have been suggested in order to compensate for that backward move of the "center of thrust."

Fig. 11 The engineer attempts to adjust the forms of the plane in such a way that it may have a natural balance when cruising; at low velocities (takeoff and landing), several methods are being used to make sure of that balance; the most efficient one is the use of a duck-shaped design (plan canard).

Fig. 12 The resistance to the forward movement of the S.T.P. depends on numerous parameters which the engineer tries to minimize; in this example, the various losses due to a "nonoptimalized" design of the plane have been evaluated.

Fig. 13 The propulsion system of the S.T.P. is much more complex than that of a present-day "jet" since high efficiency (i.e. a low fuel consumption) is required at all flight speeds (takeoff, climbing, supersonic cruising, holding, etc.); the thermic yield of an engine increases with the speed, and that makes it possible to compensate for the decrease of the aerodynamic fineness in the supersonic field; finally, the choice of the cycle of the engine (simple or double flow jet, "dry" or with postcombustion; turbo-ramjet engine) depends primarily on the cruising speed but also on the thrust required to pass the sound barrier at a sufficient altitude (so that the supersonic "bang" sound will be tolerable on the ground).

Fig. 14 The engine yield is closely related to the effectiveness of the airscoop of the jet engine; consequently, there is a need for compressing the air through multiple shock waves by means of profiles that can be adjusted in accordance with the flight velocity; when a Mach number of 3 is approached, the "natural" compression will be sufficient so that it will then be possible to do away with the classical compressor and to burn the fuel directly in order to heat the air above the jet outlet (solution of the "ram-jet" engine).

Fig. 15 Description of a transatlantic flight at a Mach number of 2.2, in slightly more than three hours; the distances covered at subsonic speed (climbing, descending, holding, diversions) require almost half the fuel taken along; consequently, there is a need for high efficiency simultaneously at supersonic and at subsonic speeds.

Fig. 16. The thin slender wings are not very suitable to supply high lifting capacities at the time of the takeoff or landing; that is why the wing load of the S.T.P. depends, in the last analysis, on the permissible maximum speed during the approach to the runway; the solution of the "duck plane" makes it possible to improve the lifting capacity considerably (O.N.E.R.A.).

Fig. 17. The slender wings with their sharp leading edges are profiting from a considerable increase of the lifting capacity, thanks to the development of a vortex sheet which renders them, in the last analysis, acceptable for low speeds.